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Evaporative Techniques for Stormwater Runoff Alleviation

Allison M. Arnold

EVAPORATIVE TECHNIQUES FOR STORMWATER RUNOFF ALLEVIATION

Allison M. Arnold

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James E. Smith, PhD., Chair
Andrew D. Lowery, PhD.
Kenneth H. Means, PhD.

Department of Mechanical and Aerospace Engineering

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ABSTRACT

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Current climate changes have led to a projected steady increase in rainfall over the next several decades, notably in the Greater Pittsburgh Area. Even without this predicted increase the urbanization of many regions has altered local natural environments, which in the past stored, shed and evaporated this runoff water effectively, maintaining balance within the water table. These added rainfall forecasts, combined with America's growing trend to develop and expand the urbanization of our natural earth, has resulted in a growing surplus of stormwater runoff water affecting these cities and their suburbs, leaving many sanitation departments unable to meet the heightened demands of excess storm water runoff imposed upon them. Pittsburgh, Pennsylvania, in particular, has had to assume an accelerating rate of stormwater runoff from their considerable concentration of buildings and paved surfaces, which, in turn, has been diverted directly into the region's main sewage treatment plant roughly 70 times annually.

The identifiable issue of this project concerns when the amount of rainfall becomes so considerable that the remaining natural vegetation in these regions is unable to keep up with the heightened levels of rainwater being displaced. Therefore, it is the objective of this thesis to validate the concept and strategy of reevaluating effective and efficient water-handling strategies, utilized within natural environments, to urbanized regions. This will be done through the simulation of evaporative strategies implemented by "Mother Nature," in preserved natural environments. Furthermore, the evaporative roof-spray technology investigated will also be analyzed for the potential for a return on investment for contributors through energy savings and cooling effect, primarily as it pertains to the heating and cooling of infrastructure and increased productivity of the work force.

The designed system is able to collect 542,000 gallons of water in a single summer season, allowing for a potential evaporation of 375,000 gallons during the same timeframe. Apply an average evaporation rate of 2.8 gpm also allows for the evaporation of a 10,000 gallon tank in less than 5 days. The return on investment analysis shows a potential ROI of less than three years. These results supported the conclusion that evaporative technologies yield the ability to effectively offset stormwater runoff with the potential for a substantial return on investment. Because wastewater treatment plants are not equipped to handle the sudden increases in collected waste products, such technologies, applied on privately-owned properties, will work collectively to reduce the risk of overflow at treatment plants during storms or periods of heavy rainfall.

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Finally, I would like to thank my wonderful family for their unconditional love and support over the duration of my educational career. To my loving and encouraging mother, Maria Rosso Arnold, and my dedicated and motivated father, William L. Arnold Jr.: I would have never been able to succeed on this path without your constant support and guidance, thank you.

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LIST OF SYMBOLS

Symbol	Name	Unit
α	advection coefficient	N/A
A	surface area	ft^2
β	expansion coefficient	$ft/second^2$
C*	circumstantial coefficient	$ft^2/second$
cp	specific heat	Btu / lb_m * °R
d	diameter	ft
δ	thickness	ft
δ_{rain}	depth of precipitation	ft
ε	emissivity	N/A
g	acceleration/gravity	ft / $second^2$
$g(P_r)$	diffusion equation	N/A
G_r	Grashof number	N/A
$\bar{h}$	average convective heat transfer coefficient	Btu / h * ft^2 * °R
$\bar{h}_{fg}$	heat of vaporization	Btu / hr * lb_m
HP	horsepower	HP
k	thermal conductance coefficient	Btu / hr * ft * °R
K_p	permeability factor	ft / hr
L	length	ft
η	runoff collection coefficient	N/A
N_u	Nusselt number	N/A
P_r	Prandtl number	N/A
P_w	surface pressure	lb_f / ft^2
P_{ws}	surface pressure	lb_f / ft^2

P^*	circumstantial coefficient	N/A
ρ	density	lb/ft^3
Δq	heat transfer	Btu / hr
q_{evap}	heat of evaporation	Btu / hr
q_h	convection heat transfer	Btu / hr
q_k	conduction heat transfer	Btu / hr
q_{rad}	radiation heat transfer	ft-lb
q_v	volumetric saturation	N/A
Q	volumetric flowrate	ft^3/second
R	Reynolds number	N/A
R_a	Rayleigh number	N/A
σ	Stefan-Boltzmann constant	Btu / hr * ft^2 * $°R^4$
Δt	time interval	seconds
T_1	destination temperatures	°R
T_2	reference temperatures	°R
Θ	wind speed factor	N/A
Φ	humidity factor	N/A
v	velocity	ft/s
V	volume	ft^3
$V_{Collect}$	volume of precipitation	ft^3
$\dot{V}_{RZ,Loss}$	volumetric flow rate	ft^3 / second
$\dot{V}_{trans}$	rate of transmission	ft^3 / second
Ws	pump shaft power	Watts
X	surface pressure factor	N/A
X_s	saturated surface pressure factor	N/A
ζ_p	efficiency	ft H_2O

1. INTRODUCTION

Current climate changes have led to a predicted steady increase in rainfall over the next several decades [1] [2] [3]. Simultaneously, the urbanization of many regions has altered the local environment, which in the past stored, shed, and evaporated this stormwater runoff, and now must deal with it through conventional sewage treatment processes. This forecasted increase in rainfall, combined with America's growing trend to develop and expand the urbanization of our natural environment, has resulted in a growing quantity of stormwater runoff effluent affecting these cities and their suburbs, leaving many sanitation departments unable to meet the heightened demands imposed upon their sewage collection systems, resulting in the dumping of untreated sewage into natural, clean waterways. Therefore, in response to this, water and environmental preservation agencies within regions experiencing this growing stress on their wastewater treatment plants are now focusing their efforts and resources to addressing this issue. Pittsburgh, Pennsylvania, in particular, has had to assume an accelerated rate of stormwater runoff from buildings and paved surfaces, which, in turn, has been diverted directly into the region's main sewage treatment plant systems. With multiple environmental authorities within the area, Pittsburgh has been identified as the perfect candidate for this thesis research and report.

1.1 RESEARCH PROJECT OVERVIEW

The natural environment has always utilized a combination of vegetation, elevation and gradients, as well as soil absorption and percolation, in order to effectively store, redistribute, and evaporate or redirect water from episodes of heavy rainfall. For example, vegetation intercepts and retards the flow of excess rainfall, reducing its erosive energy, diminishing overland flow of runoff, and allowing infiltration, percolation, and evaporation to occur. In the natural environment, not only is the sanitation of rainwater preserved, but it is also efficiently routed, following the natural declination of land, back into natural water collectors such as lakes, rivers, streams, ponds, etc., or is captured in and around the vegetation and natural ground outcrops. But, as land is urbanized, there is a decreased opportunity for this natural process to occur, as all of these processes are altered, and the net result is a significant increase in storm water runoff volume [4]. This runoff is not constrained, restricted or re-directed, within these man-made systems and so the water collects quickly and the runoff is concentrated in a period of time relative to that of the natural process. As a result, the rain is deflected from the buildings, parking lots, and other man-made structures, often polluting water with residual debris, and redirecting it in ways that can be harmful to the preservation of natural ecosystems and the waterways.

Topsoil and other debris picked up by rainwater runoff is forced to flow towards and is deposited into rivers and streams causing considerable water quality problems (i.e. water clarity and purity is affected) [5]. As stormwater flows across streets, parking lots, buildings, and through thin grassy fields, runoff will begin to accumulate and carry toxic substances and oils such as fertilizers, pesticides, heavy metals, salts and other chemicals [6, 7] [5]. Furthermore, not only does excess runoff translate into compounding issues at regional wastewater treatment facilities, but this, in combination with the reduced vegetation of urban regions, also allows for significant erosion issues over time [5]. It was noted in the Encyclopedia of Energy Technology and the Environment; "In the future, water quality management, in highly urbanized areas, will have to consider stormwater as a major pollutant" [8].

The Third National Climate Assessment published in 2014, indicated that the United States' Northeast Climate region has "experienced a greater recent increase in extreme precipitation than any other region in the U.S., and that "between 1958 and 2010, the Northeast saw more than a 70% increase in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events)" [9]. In addition, increases in heavy precipitation events are evident in every other climate region across the continental United States [10]. Between 1895 and 2011, precipitation in the Northeast region has increased by nearly half an inch per decade and temperatures have been increasing at a rate of 0.16°F per decade [9]. A National Oceanic and Atmospheric Administration (NOAA) evaluation of average monthly precipitation trends between 1955 and 2015 reveals that the most substantial precipitation increase occurs in June for that 60 year period. This monthly trend not only occurs in the Pennsylvania Southwest Plateau climate division as well as in the localized Pittsburgh area [11]. Although precipitation models are less determinate than other climate models, heavy precipitation events are expected to continue to increase in frequency throughout the next few decades [10] [12] [13]. This is also specifically applicable to the Pittsburgh, Pennsylvania region. Not only is Pennsylvania predicted to experience an increase in precipitation statewide by 7-10% over the next 65 years, but it is also projected that the state will likely see an increase of at least 3.5°F [1] [2] [3]. Furthermore, as the state begins to experience more days over 90°F, it is also expected that there will be an increase in "precipitation extremes" resulting in more frequent occurrences of severe rainstorms, such as downpours, and drought [1] [14]. Rainwater runoff is predominantly captured by the primary sewage systems in larger and more developed population centers. This places substantial demand on local treatment plant's abilities to capture and clean the collected sewage.

Recognizing that the regional wastewater treatment plants are overwhelmed by more and more influent collected annually, it has become the primary focus of many organizations, such as the Allegheny County Conservation District and Regional Industrial Development Corporation (RIDC), to research and implement solutions that will work reduce the amount of excess stormwater runoff polluting the environment and natural waterways. Furthermore, a more ambitious approach is to encourage and develop technologies that also implement energy-recycling strategies that utilize the, once harmful, stormwater for more productive solutions that yield a return on investment.

1.2 GENESIS OF THE PROJECT

This research and design effort was introduced by Jan Lauer, the director of the Allegheny County Conservation District, to help develop ideas towards the mitigation of the effects of excess storm water runoff in the Greater Pittsburgh Area. The preferred and selected assignment was to evaluate an evaporative technology that could be used for the capturing of rainwater to be utilized as a cooling medium for the roofs of large industrial shops and warehouses and the parking lots and storage areas servicing these facilities. Similar methods have been used in warmer climate regions, such as Arizona, but because they used city-processed water, in contrast to this report's proposed usage of storm water, they failed to produce a sufficient return on investment when compared to conventional air conditioning.

In order to better understand the problem proposed, methods normally implemented by the natural environment to efficiently redirect and redistribute stormwater, were evaluated. From this analysis, it was gathered that a major component of this process revolves around the ability of plants and soil to allow for proper and effective evaporation of collecting rainwater. It was for this reason that this research study focused on evaporative technologies that could be utilized to “mimic” natural evaporative processes within an urbanized environment. Further investigations into evaporative science and technology revealed that the evaporative process of changing water from a solid state to a gas state yields a cooling element that can be utilized to cool surfaces and/or structures.

The research to be evaluated by this thesis was thus dubbed “Evaporative Cooling Techniques” and the selected system that exemplifies its strategies is the “Evaporative Roof-spray Technology.” These techniques, though preferred for large-scale warehouse type commercial structures, can be implemented on local and large scale applications within urbanized regions.

Of the green-evaporative technologies, spray-roof cooling systems have proven to be highly effective at, not only repurposing collected rainfall, but are also capable of reducing costly energy expenses through their ability to cool building interiors, reducing the need for air conditioning or other fuel-consuming cooling methods. As environmental regulations become more stringent, environmentally conscious technologies will need to be developed in order to provide private and public land owners with solutions to accommodate the heightened legal demands, while yielding the potential to offer a return for the investor.

It is this thesis’s hypothesis that the utilization of grey stormwater in combination with the appropriate installation of these evaporative cooling techniques would yield a substantial potential return on investment, competitive with air conditioning and other current non-environmentally contentious technologies, when applied to large commercial structures. Furthermore, the systems ability offset runoff from entering the primary collection system will allow for other potential returns in the form of tax credits or reprieves from fines.

With the goal of reusing storm water runoff in an energy saving method, the approach for this project was to interact with the sponsor(s) and to provide a simple design considerations for the capture and re-distribution of rainwater with a system to contain and capture the water runoff and to then spray it, in a misting or similar action, on the roof of a building to allow evaporation to occur and, in turn, cool the interior of the building while reducing the amount of storm water runoff to be captured by the sewage system. Portions of this work were completed under a summer course in the initial response to this request by the Allegheny Conservation District. As a participant in this project, elements from this first study have been utilized throughout this research study as a continuation of the efforts of those past works. Furthermore, to provide a working example for this thesis the test structure from this initial study was selected for this evaluation located in Monroeville, Pennsylvania.

1.3 PROBLEM STATEMENT

It is the intent of this thesis to investigate strategies utilized by the natural environment to properly redirect, collect, store, and utilize stormwater runoff. This research endeavor is to provide a method of stormwater overflow reduction through the utilization of evaporative cooling techniques utilized in spray-roof technologies in order to address the water-pollution effects of increasing stormwater runoff. Capturing a portion of the excess stormwater runoff and using it in an evaporative process, allows it to be used in a method that returns it to the environment in ways that it would if this area was left naturally preserved. Furthermore, the utilization of evaporative cooling methods allows for further usage of the collected stormwater as a cooling agent for buildings and structures with large roof surface areas. Using evaporative cooling to reduce the temperature of the building incurs some costs for installation and maintenance, but it is postulated that the potential return on investment from its implementation is significant. In direct response to the increasing sewage overflow issues faced by Pennsylvania wastewater treatment plants, such technologies would work to reduce the downstream sewage effluent. Furthermore, not only can evaporative technologies be used in heating and cooling applications, but this can also be utilized to increase worker productivity through the utilization of more comfortable work-environment temperatures.

1.4 RESEARCH OBJECTIVE

The objective of this work is to evaluate the needs associated with stormwater runoff and the mitigation potential for employing the collection, storage, filtration, and rooftop distribution for an Evaporative Roof-spray Cooling System in order to reduce the environmental impact of the excess stormwater runoff problem. Through the evaluation of current metrological conditions, such as rainfall, this thesis will design and evaluate an Evaporative Roof-Spray System for its ability to reduce the amount of stormwater runoff. Additionally, this report intends investigate returns on investment through the research of productivity versus temperature, electrical cooling savings, and tax reprieves.

2. LITERATURE REVIEW

In order to fully understand the research behind evaporative roof-spray cooling techniques a literature review was conducted to evaluate the technology's history. Therefore, this section will evaluate (1) the historical review, which encompasses notable prior studies and experiments, the history of the technology, patent reviews, and climate evaluations; (2) regional and building legislature regarding water quality standards, which will explain the current classifications and definitions of water quality standards and current codes and regulations currently in effect nationally and for Monroeville; and finally (3) the test site background information, which will outline the test site and region being evaluated.

2.1 HISTORICAL REVIEW

Stormwater Management (SWM) is a "mechanism for controlling stormwater runoff for the purposes of reducing downstream erosion and flooding, and mitigating the negative effects resulting from urbanization" [15]. In order to properly design stormwater management systems for regions it is important to first define and understand the issues regarding runoff. Rainfall is defined as "the quantity of water, expressed in inches, precipitated in the form of rain, snow, or sleet" [16]. Runoff occurs when the rainfall is no longer absorbed by the soil and/or other surfaces [16]. Because rainfall is unique every season and every time it occurs, runoff is also unique. Precipitation also varies seasonally or even within individual storm event and is typically dictated by prevailing climate conditions for that time of the year [15]. When analyzing runoff various surface conditions come into effect such as soil type and condition, topography, amount of live vegetation, and land usage; all of which must be considered within larger stormwater management designs such as detention ponds, major culverts, or determining the floodplain [15]. Design Storms, or recurrence intervals, refer to a statistically estimated rainfall-runoff event used in the design of hydraulic systems. These are not actual storms, rather, they are "fabrications intended to represent the characteristics of average storms for particular regions of interest" [15]. Further runoff evaluations delve into the effects of sleet and snow and their associated overflow. Because there is some variation in the evaluation and calculation of snow or sleet from rain, these two meteorological possibilities were neglected for this study and the focus, therefore, will concern the effects of rainfall and how to measure its runoff capabilities. More notably, this will consider rainfall events as they are described in terms of depth, duration, and frequency of occurrence [15].

As noted prior, runoff is primarily affected by surface conditions. Changing lands for residential and commercial uses inevitably results in "a decrease in pervious surfaces and an increase in impervious surfaces." This then results in a change in the hydrologic and hydraulic characteristics of the watershed. When the amount of generated runoff from impermeable surfaces becomes so excessive that the remaining natural vegetation is unable to keep up with the heightened levels of rainwater now being displaced, the result is an overwhelming amount of sewage collection at regional wastewater treatment plants. Furthermore, these alterations to the basin imperviousness results in "increased flow rates, increased runoff volume, and an increase in the frequency of flooding and degradation of surface water quality" [15]. It should also be noted that common city-development practices encourage the excess water to seek outlets through the main sewage collection system. In turn, as the towns of the Allegheny region and the Greater Pittsburgh Area continue to develop, their ability to naturally and effectively reroute excess runoff back into the environment responsibly becomes more and more difficult.

When collected sewage exceeds the max containment volume of the collection basins, the resulting overflow of raw sewage is dumped directly into natural waterways. Because of this, regions that experience unusually high, and/or unpredictable, levels of rainfall and rain-storms tend to overstress their regional wastewater treatment plants, resulting in excessive overflows, increases in the amount of raw sewage polluting natural waterways, and, in turn, a surplus of costly fines being imposed on the region, wastewater facility, and public. Currently, there are about 70 days out of the year when contact with river water in the Pittsburgh area is not recommended due to combined or sanitary sewer overflows [17]. With the maximum capacity of the current Allegheny County Sanitary Authority facilities already stressed beyond 250 million gallons of wastewater daily these rain storms cause consistent fresh water pollution through excess effluent dumping into the Ohio River [18] [19]. Even if the treatment centers were to invest in additional capacity, the amount required to handle the runoff from sudden, and typically unpredictably large storms, would cause these facilities to be overdesigned and inefficient for normal conditions. It is for this reason that the initiative has been taken towards investigating alternative solutions that implement more effective and efficient strategies for water conservation and handling. This generated research into evaporative techniques, which has further uncovered the potential for cooling benefits for large structures, more notably through Evaporative Roof-Spray Technologies.

2.1.1. NOTABLE PRIOR STUDIES AND EXPERIMENTS, RELATED TO EVAPORATIVE ROOF-SPRAY TECHNOLOGY AND TECHNIQUES

Several studies and technological evaluations have been initiated and conducted from this generated interest to harness the cooling potential within evaporative properties and processes. For example, Robert and Stall, 1967, evaluated the evaporation from a lake surface can be modeled/calculated through the utilization for the water budget method, mass transfer method, and energy budget method. It was understood from these works that the net evaporation loss from a lake, should equate to a difference between the maximum expected gross lake evaporation and maximum expected precipitation [7]. Another study, conducted by Shuttleworth (1993) developed a method to model the evaporation and transpiration from soil surfaces and crops [7].

Experiments conducted by Yellot evaluated the use of “intermittent water sprays on poorly insulated roofs” [20]. His work demonstrated that, “the usefulness of water sprays in reducing discomfort levels in cases where the costs of conventional air condition would be prohibitive” [21] [20]. It must be noted, though that this study neglected the effects of relative humidity. Unfortunately, that also means this study neglected a significant factor in the evaporative calculations associated with spray roof technology. Figures 2-1 and 2-2 demonstrate the relationship between water surface temperature, heat flux, and relative humidity. Further studies conducted by Jan and Rao investigated the effects of evaporative cooling on roofs of both conditioned and unconditioned buildings [22]. They also evaluated several forms of water application including a “roof pond, roof-spray, and wetted gunny bags for Thick Reinforced Concrete (RCC) roofs” [22]. This study further verified the grounds for research into the degree of effectiveness in cooling that spray roof technologies yield. This experiment also found that the best methods of water application, in order of effectiveness, were the gunny bag, roof-spray, and then roof pond [22] [21].

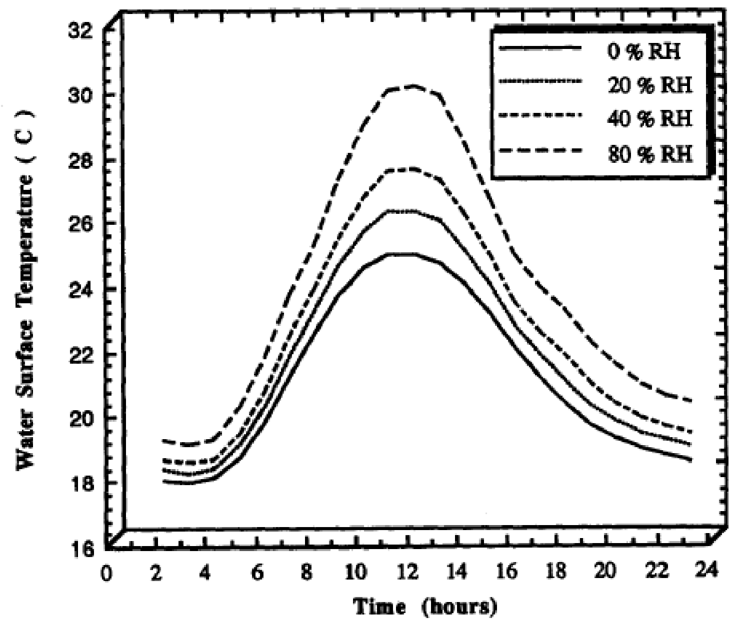


Figure 2-1: Change in water surface temperature when exposed to environments with varying relative humidity [21]

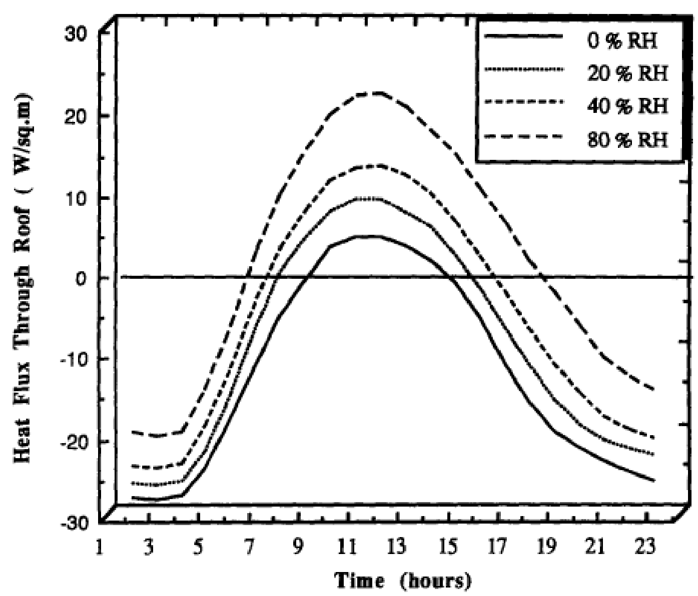


Figure 2-2: Heat flux in varying relative humidity [21]

With summer month dry rooftop temperatures reaching as high as 160°F, or higher if it is a darker colored roof, evaporative roof cooling systems are a simple option for offering cooling insulation and reduced cooling costs to structures with larger roof surface areas [23]. The evaporative process allows water to draw energy from whatever surface it comes into contact with, in this case the rooftop. As stated by a study evaluating evaporative roof cooling potential, "every pound of water that is evaporated absorbs approximately 1000 Btu of heat" [23]. This means that, "during a typical summer in the south" the amount of energy absorbed by the water during this evaporation process can result in a "40°F to 60°F reduction in the roof surface temperature" [23]. In a more recent experimental study by Carrasco it was found that "roof-spraying methods led to a 60% reduction in the heat flux through the roof, as well as a 20% drop in the roof's surface temperature [24]. It was also found that there was a substantial reduction in the interior temperatures of the storage structure tested" [24] [21] [13].

2.1.2. THE HISTORY OF ROOF-SPRAY TECHNOLOGY

With ever increasing focus on our society's pollution imprint on the Earth, green and energy efforts have continued to promote cost effective technologies. Among these is an increased interest in reducing the high costs of air conditioning through heat reduction technologies [23]. Evaporative Roof Cooling Systems or "roof-spray systems" were first introduced in the United States in 1934 [23]. "A "mini-boom" for roof-sprays existed following World War II, when air conditioning was new and in short supply," and the textile companies further drove this as a cheaper alternative to air conditioning for humidity control [23]. As the cost of air conditioning in the fifties and sixties became more reasonable, with minimal operating costs, roof-spray technology lost support and was "retired" [23]. The "energy crisis" of 1973 to 1974 refocused American industries towards the need to conserve energy, due, in part, to the now pricey electricity costs both financially and environmentally. Reviewing the documentations on retrofit installations of spray-roof technologies, it can be shown that direct energy savings and paybacks are notable over the course of twelve to thirty months [23]. A sample summary of the cost savings for this evaluation can be seen in Table 2-1 below [23].

Table 2-1: R.R. Abernethy, Inc. Summary of Cost Savings [23]

Summary of Cost Savings	
Demand Charge Savings	$12,420.00
Direct Energy Savings	$9,480.00
Subtotal Savings	$21,900.00
Less Water Cost	-$1,854.00
Less Maintenance 1st Year	$515.00
Annual Savings	$19,531.00

In these past technology developments and testing, the most expensive operating cost consumed by the Evaporative Roof Cooling System (ERCS) is water, even though it is considered one of the "most economical refrigerants" on the market [23]. This means that, if the cost for water utilized in the systems were to be reduced then the effective return on investment for such retrofits may, in actuality, be more considerable than what was previously understood. It is from this opportunity for enhanced effectiveness and return on investment that our proposed ERCS model was spawned, code attached in Appendix F.

"In buildings, which are not air conditioned, the effect of evaporative cooling as a result of roof-spraying technology is quite substantial" [21]. The principle underlying this technology is quite straightforward. The water sprayed onto a hot roof cools the roof as the water evaporates when the roof temperatures are excessive. In turn, the amount of heat removed from the roof, which is equivalent to the latent heat of vaporization of water, will reduce the heat flux through the roof, reducing its effects on the air-conditioned interior within [21].

Interest in the exploration of the Evaporative Spray Roof Cooling (ESRC) applications and technologies was found validated through investigations into existing patented technologies. There are currently several existing patents related to this concept. Investigations were made into understanding these patents, their relevance to this project's objectives, as well as what can be done to build from these technologies that has not yet been accomplished [13].

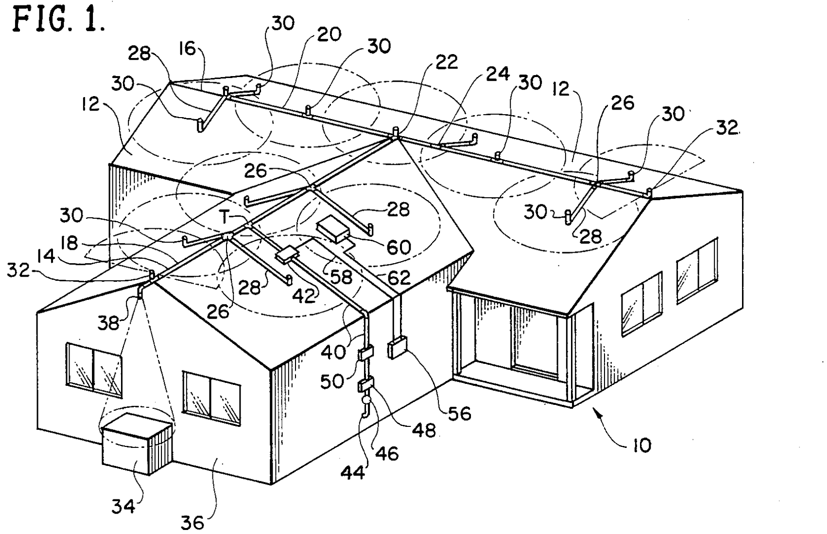
2.1.3. PATENT HISTORY

There are many current patents related to the treatment of water and to the evaporation of untreated water, unfortunately these are typically not directly applicable to stormwater applications in relation to evaporative roof-spray technologies. Furthermore, most patent research will result in more investigations relating to "evaporative cooling" or alternative environmentally-oriented technologies such as permeable concrete, roof tile and garden schemes, corrugated pipe systems, or storm water basin modifications, rather than roof-spray applications. Therefore, several patents were found and reviewed as they relate to evaporative cooling technology, and the associated apparatus' associated with evaporative cooling through spray systems and evaporative roof spray installations.

Four of the identified patents specifically related to this research were found to be expired and focused around variations of different pumping mechanisms to regulate how much water would be applied to a roof as well as designing the piping layout, pressure, temperature gauges, and spraying mechanics. Although these are listed as US patents, most of the more recent patents filed also have been granted European, German and/or world publications. The most recent patents directly evaluating Evaporative Spray-Roof Cooling (ESRC) systems was Patent # 4,761,965, applied for by Stephen G. Viner in 1987, and was essentially a contemporary adaptation of Patent # 2,506,936 [25] [26]. Images from Viner's patent can be seen in Figures 2-3 and 2-4. The original patent # 2,506,936, applied for by Alfred T. Murray, shown in Figure 2-5, is for an ESRC system with a more formal grid like system of tubes and distributor devices (such as sprinkler heads) in a manner that the application of the water onto the roof surface would be more efficient in removing heat from the building [26]. Additionally, this patent featured an electronic control system that governed how often the system would spray the roof surface, preventing flooding [26]. The newer adaptation in 1987 took this a step further by utilizing thermistors encased in epoxy, arranged about the roof's surface to monitor the temperature distribution, and in turn, allowing for the application of water to specific areas in discretized quantities in order to further minimize the amount of water expended in operation [25].

U.S. Patent Aug. 9, 1988 Sheet 1 of 2 **4,761,965**

FIG. 1.



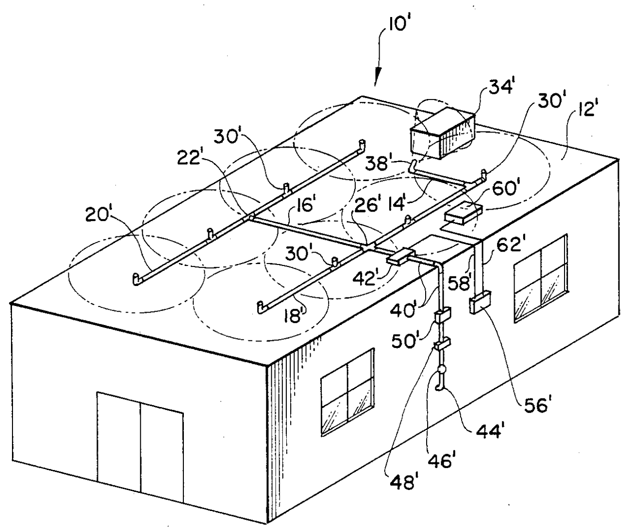


FIG. 2.

Figure 2-3: US Patent #4,761,965 Associated Diagrams of "Evaporative Roof Cooling System" (1 of 2) [25]

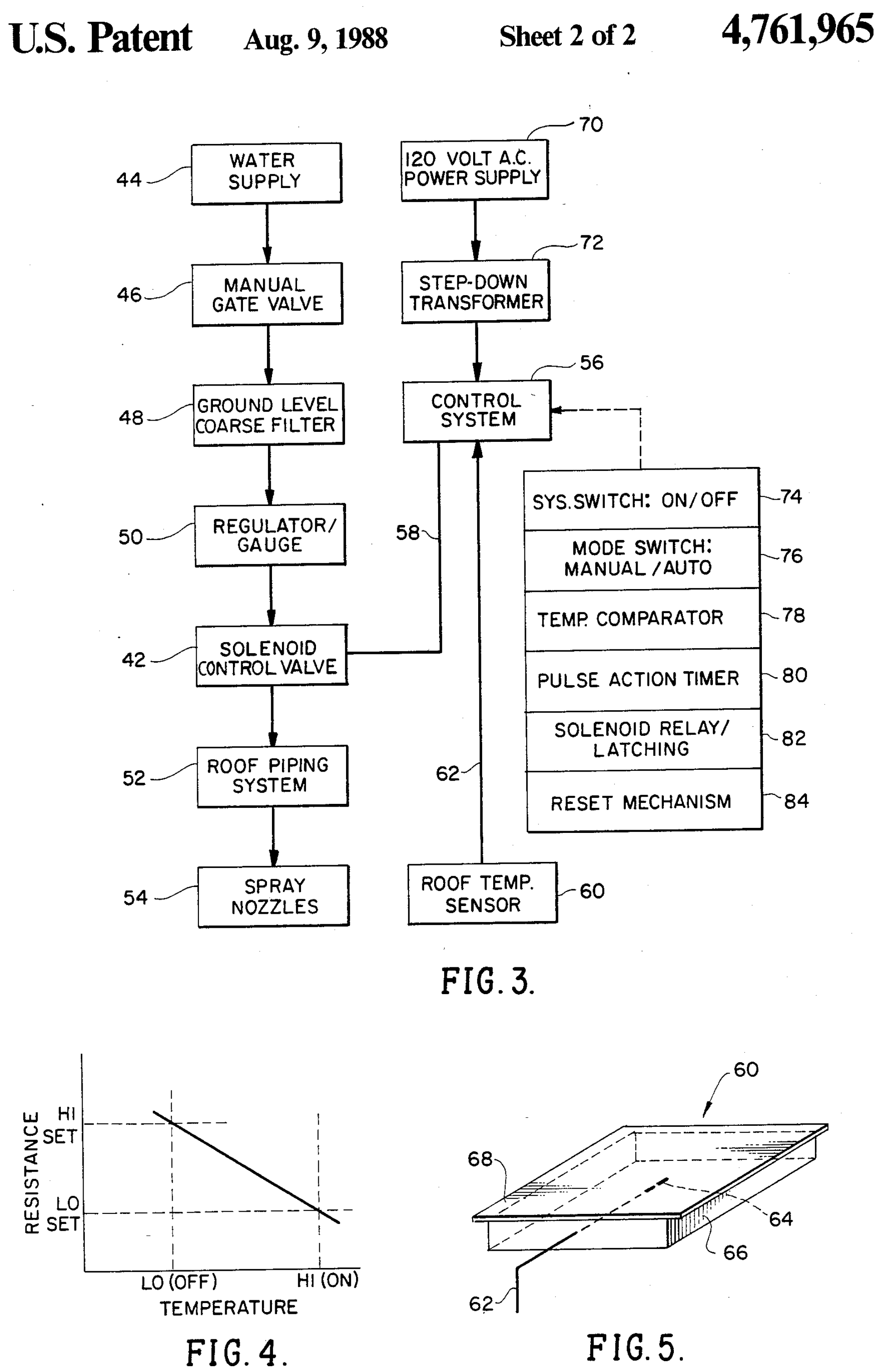


Figure 2-4: US Patent #4,761,965 Associated Diagrams of “Evaporative Roof Cooling System” (2 of 2) [25]

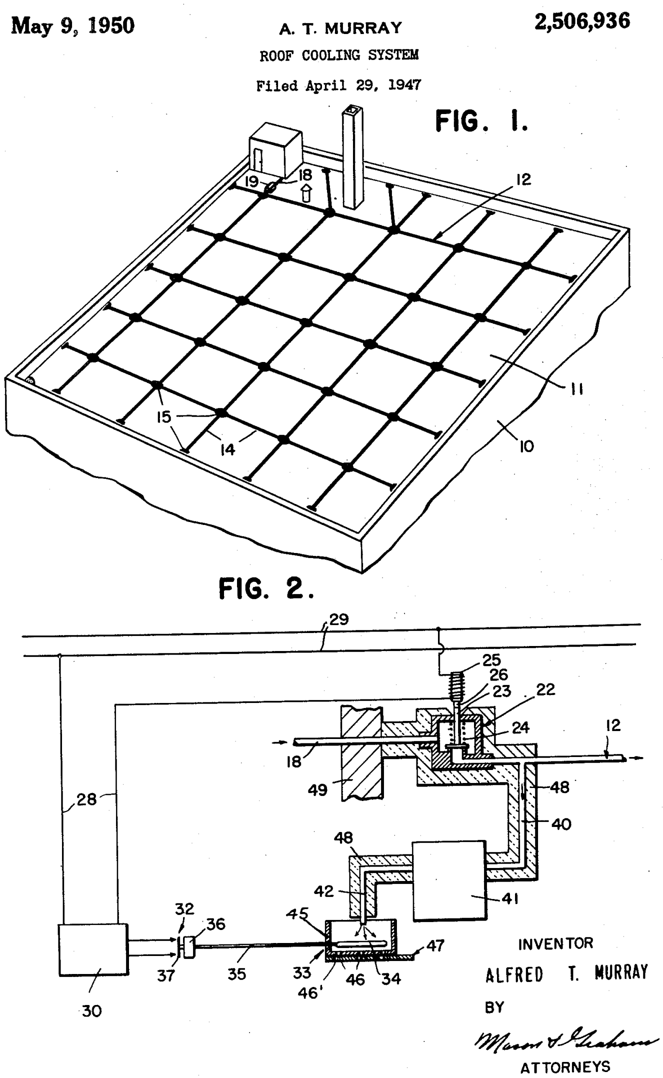


Figure 2-5: US Patent #2,506,936 Associated Diagrams of Evaporative Roof Cooling Technology Design [26]

Researching further, additional US Patents were developed surrounding the delivery system and apparatus design. US Patent #5,724,824 A, by David A. Parsons developed an evaporative cooling delivery control system which could be implemented in an Evaporative Roof-Spray System [27]. This system defined using a combination of a water supply tank, an air compressor, solenoid valve, and electric control module for operation of the valve and compressor [27]. US Patent #5,598,719, by Michael Jones and Mark Hensley for an Evaporative Cooling Apparatus, designs the equipment and system to be installed for a multitude evaporative cooling applications, beyond the scope of only roof-spray cooling [28]. This evaporative cooling unit includes an internal conduit structure with corresponding inlets and outlets to allow for forced air to be applied in combination with a series of nozzles that emit atomized water into the air [28]. Unfortunately this system also relies on costly tap water as the primary refrigerant. Patents beyond these span into the realm of equipment cooling applications.

Additional patents discussed pressure regulations and spray analysis, such as US Patent #6,141,986 A by Edward Koplin, who designed a nozzle system to work as an evaporative cooler (see Figure 2-6) [29]. Patent # 2,437,156 [30], applied for by the inventor Albion N. Frick, was granted on 2 May 1948 and utilized a reservoir to generate pressure via the expansion of a gas due to higher temperatures, thus applying a spray of water to the roof. It was found that this technology is not very accurate or efficient compared to what modern alternatives might achieve, given the advancement of programmable logic control circuitry and digital thermometers and thermal sensors, but at the time it was a way to passively cool the roof [30]. Patent # 2,554,409 [31], shown in Figure 2-7, applied for by Leonard H. Holder in 1948, improved upon a previous patent by the same person by describing a spray device that required significantly less maintenance than a standard sprinkler head because of a pair of unique features [31]. First, it had a specially designed nozzle, which kept the spray in a constrained pattern so as to cover a consistent area (and thus maintain performance and efficiency). Second, it had a self-flushing capability, wherein the system could be instructed to run at a higher pressure. The interior design of these spray devices would expand under the pressure, flushing any debris that might otherwise clog the device [13].

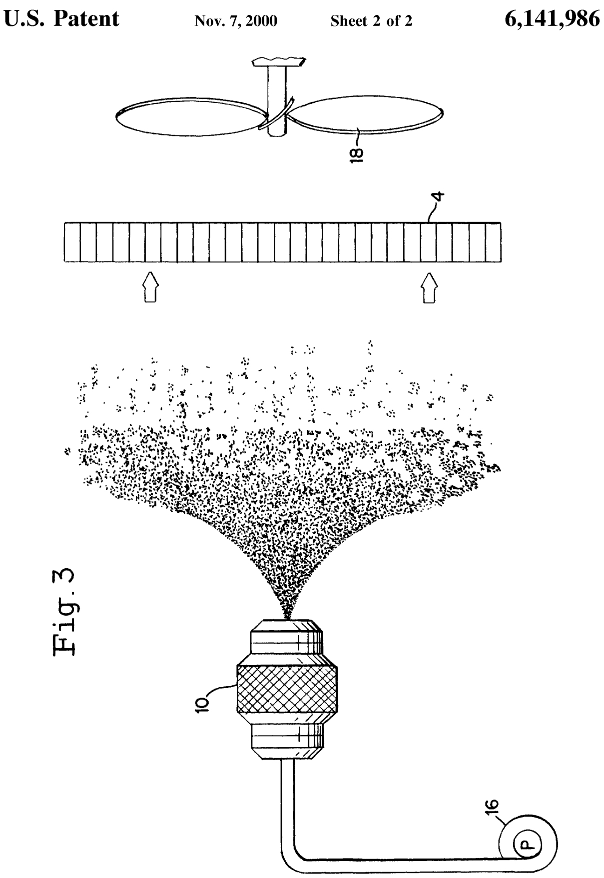


Figure 2-6: US Patent # 6,141,986
Nozzle for Indirect Supplemental Evaporation Cooler [30]

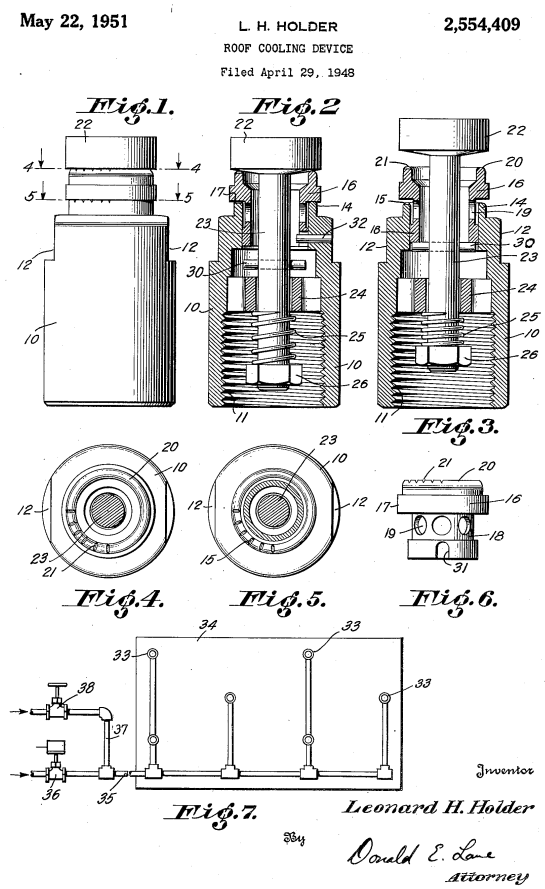


Figure 2-7: US Patent # 2,554,409
Diagram of Method and Apparatus for Cooling by Evaporation [31]

2.1.4. CLIMATE

According to the Municipality of Monroeville, PA; "stormwater management facilities on all development sites are expected to control the peak stormwater discharge for the two-, ten-, twenty-five- and one-hundred-year storm frequencies" [32]. Therefore these storms were evaluated based on the the NOAA's Hydro meteorological Design Studies Center (HDSC) statistical analysis for the Monroeville area. This data predicts that definitive heavy rainfall events (≥ 2 *inches*) should occur only once each year, and are to be referred to as the "1-year storm" [33] [34]. Figure 2-8, below, analyzes the Monroeville region for a range of these "recurrence-interval" rainfall episodes, denoted as 1-Year through 100-Year storms. The second storm analyzed in this thesis is the 25-year storm. As can be seen in Figure 2-8, this storm generates 4 inches of precipitation over a 24 hour time frame. It should be noted, though, the statistic designation also allows that these events may occur more than once in a much shorter period.

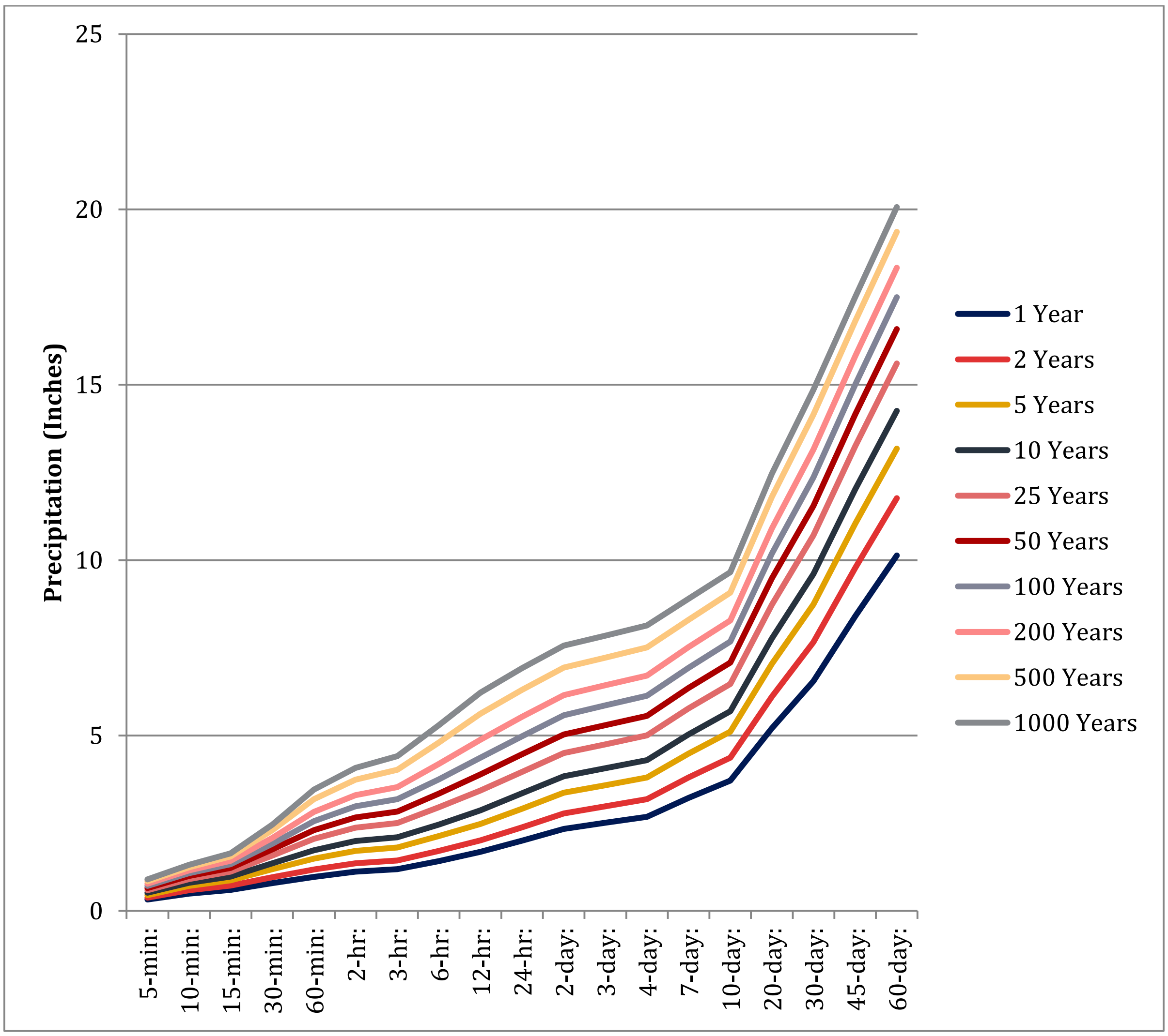


Figure 2-8: Precipitation Frequencies, Monroeville, PA [37]

2.2 REGIONAL & BUILDING EPA REGULATIONS REGARDING WATER QUALITY STANDARDS

Many localities have ordinances that enforce regulations that act to mitigate potential damages to the water cycle and watershed resulting from urbanization [15]. This includes factors such as erosion and sediment control, stormwater retention and detention ponds, among other developed Best Management Practices (BMPs), or techniques used to control non-point source pollution [15]. It is important to consider these regulations in any regional technology development so as to ensure its proper integration and effective impact into said society. As the concept of "stormwater management" has become more fully defined society has responded with creating water quality standards and legislatures that work to encourage the preservation of natural clean waters. Because of this, successful stormwater management technologies must uphold/meet certain water quality standards, which have been supported by EPA legislatures and civil laws.

2.2.1. DEFINING WATER QUALITY STANDARDS

As concern grew for the deterioration of the quality of our natural waterways and the water table, environmentally aware organizations, such as the Environmental Protection Agency (EPA) began evaluating how to limit the amount of pollution being exposed to the water system, as well as our treatment of polluted waters, and how to classify the quality of the water. After establishing water quality classifications, legislatures were created for the regulation and establishment of the proper use and maintenance of said water types. In order to design stormwater runoff handling techniques, such as evaporative roof-spray technologies, it is important to understand, not only what quality of water the system involves, but also what legalities must be overcome in order to endorse, integrate, and promote the technology within society. More specifically, in order to properly evaluate and select the filtration component of this system, these legislations and classifications concerning water quality must be understood.

2.2.2. EPA CLASSIFICATION OF WATER

Sanitary Analysis, i.e. the evaluation of water for its ability to be used for public supply, quickly became a key factor in the understanding of water quality and pollution. Water quality, as defined by the EPA, became known as White, Grey, and/or Black Water. Additionally, pollution sources were established and labeled as either point or nonpoint sources. Point sources of pollution pertain to one source, like a pipe, whereas nonpoint sources pertain to a large area [23] [35].

The three main classifications of water, denoted as black, grey, and white, all can be collected as a result of rainfall or utility usage. Black water is defined as water having contact with fecal waste, sewage, or other dangerous toxicants; grey water may contain cooking waste, oils, fats, dirt, soap or sediments; and white water is regarded as the "tap water" quality classification. For this study it was assumed that grey water would be the appropriate classification of water to be utilized by the roof-spray technology. Therefore, design parameters followed the EPA's definition and classification for grey water. While water may be initially characterized by one of these classifications, grey water, after remaining stagnant, can give rise to bacterial and pathogen growth within 24 hours, developing into black water [36] [13]. Very quickly, these small amounts of bacteria will then spread and contaminate the entire storage vessel. Highly polluted water, or black water, cannot be used though, due to its dangerous degree of pollution, this water must be diverted towards the nearest sewer and sent to treatment facility. However, if proper steps of filtration are taken, the life of the water can be preserved at the status of grey water for longer timeframes ranging from weeks to months [37].

2.2.3. GENERAL LEGISLATIVE WATER QUALITY STANDARDS

Though organizations like the EPA and legislatures such as the Clean Water Act of 1972 have worked to create a uniform standard for the quality of water in our nation, what actually goes into the maintenance of water quality and stream standards is commonly subject to change with the municipal controlling said region and industrial environment that region has developed and is responsible for [38]. Following suit, quality standards of Pennsylvania establishes that the water is not allowed to contain materials with concentration able to effectively harm plant, animal, aquatic, or human life from nonpoint or point source discharges. Water runoff from parking lots and/or other impervious materials (rooftops, pavement) builds up chemicals and sediments that could negatively affect the water quality and is known as stormwater [39]. Materials in the water include but are not limited to, grease, scum, oil, floating materials, and other materials that can allow for formation of deposits and change in color, tastes, and/or odors; all of which may contribute to the contamination of grey water, deteriorating it to the status of black water [40] [38]. As a nonpoint source in urbanized regions, stormwater runoff is found to commonly house dust, engine oil, animal feces, and other human made and natural debris. When the location is moved from an urban area to industrial and construction areas, the water runoff commonly houses more chemicals and toxicants [41] [35] [13].

Over time, as attention has been drawn to the treatment of our water table and watershed, several "surface water drainage" oriented civil laws have become developed and widely accepted in construction and infrastructural practice. These legislatures are outlined in Table 2-2 [15] [16]. It should be noted that several "grey areas" overlap between these rules. For example, how is one to define "reasonably increased" flows passing from one property to the next? It is for reasons such as these that these rules become more symbolic as "guidelines" as their authority becomes diminished by the lack of clarity within the rule's description.

Table 2-2: List of Common Civil Rules and their Key Constituents [15] [16]

Common Enemy Rule	- Diffused surface waters are an enemy common to all property owners. - "The landowner is allowed to take whatever measures necessary to repel or expel diffused surface water effectively, regardless of damages to neighboring properties."
The Civil Law Rule	- Sections of land are granted an easement (allowance to affect or utilize someone else's land for a specified purpose) for the natural drainage to flow across - Downstream landowners must take the natural flow from upper lands - Landowners "may not obstruct, divert, or collect surface water such that it flows from his land in unusual quantities to the detriment of the downstream landowner"
The Reasonable Use Rule	- Uses civil law and common enemy rules - Under this pretext: "diffused surface waters may be obstructed and diverted if done without malice or negligence and the obstruction or diversion is incidental to ordinary use, improvement or protection of the land"

It should also be noted that, though legislations have been passed to tackle this issue of polluting our planet's finite water resources, it has become painfully aware to these organizations that it is very difficult to administer and control stream standards in an expanding industrial and urban area. Furthermore, it was found that "equitable allocation of pollution loads for industrial and municipal complexes" also pose substantial political and economic difficulties [8]. It is for this reason that this thesis seeks the approach of encouraging consumer involvement in the preservation of our natural water and waterways.

2.2.4. MONROEVILLE CODES & REGULATIONS

The main violation for the sewers and sewage disposal in the Monroeville area states "the drainage of rainwater or surface water into the sanitary sewer system into any private sewer, which ultimately discharges into the sewer system, is prohibited. In addition, the only buildings that not required to connect into the system are those erected on property with municipal sewers available to it" [32]. This means that any future developments for the Monroeville region must be constructed with integrated stormwater management systems in order to offset this runoff from entering the primary sewage collection system.

These regulations then continue to define what protocols are to be upheld for those now required to integrate stormwater management performance standards. The Municipality of Monroeville, PA law states that "any landowner and any person engaging in the alteration or development of land which may affect stormwater…shall implement measures that are required to: (1) assure the maximum rate of stormwater runoff is not greater after development than prior; (2) manage the quantity, velocity, and direction of resulting stormwater runoff in a way that adequately protects health and safety and must consider all stormwater runoff flowing over the site; and finally (3) no discharge of toxic materials shall enter any stormwater management system" [32]. If any landowner violates any of these regulations they can be then subjected to several fines or penalties.

The Monroeville Municipality's legislature outlines enforcement remedies, violations, and penalties associated with these stormwater regulations which are invoked every day the violation is committed, with each of these occurrences counting as a separate offenses. It states "any person who has violated or knowingly permitted the violation of the provisions of this law…are subjected to civil enforcement proceedings, and must pau a fine not less than $50 and not more than $500 plus court costs, including attorney's fees incurred by the Municipality" [32] . Other violations, concerning the suspension and revocation of permits and approvals, establishes that "any person violating the provisions of the article shall be guilty of a misdemeanor and upon conviction shall be subject or fined no more than $1,000 for each violation, recoverable with costs, or imprisonment of not more than 30 days, or both" [32].

Regarding the collection aspect of this Evaporative Spray-Roof retrofit, it was found that certain discharges from roof drains were not allowed. This included variations of roof drains, which are prohibited from being connected to streets, sanitary or storm sewers, or roadside ditches. This means that it has been deemed unacceptable by the City of Monroeville for stormwater to enter the main sewage collection system, rather it is to be rerouted into the designated, but separate, storm-drain system to be handled more effectively [32]. Furthermore, roof drains shall discharge to infiltration areas or vegetative best management practices to the maximum extent practicable.

2.3 TEST SITE BACKGROUND

2.3.1. GEOGRAPHIC INFORMATION

The focus of this effort was to evaluate the Monroeville region of Allegheny County as a demonstration site for potential application of the techniques covered in this research study. Monroeville is located about 15 miles east of Pittsburgh. It is a suburbia region featuring an intermingled mixture of residential and commercial developments. Monroeville's population is currently documented at 28,386 people, with Allegheny County, as a whole, containing roughly 1,231,225 residents, making it the second most populous county in Pennsylvania, following Philadelphia [42] [13]. Allegheny County has a total area of 745 square miles; of which 730 square miles is land and 14 square miles is water [43]. The county gets a total of about 48 inches of rain per year. The region's summer season experiences about 130 precipitation days per year coupled with an average high temperature of 85°F [44] [42]. The average low temperature during the summer months is 62°F [4] [44] [42]. The Allegheny River drains an area of roughly 11,500 mi^2 in southwestern NY and western PA. Average discharge is 19.680 ft^3/s and Allegheny joins the Monongahela River to form the Ohio River.

2.3.2. ALLEGHENY COUNTY SANITARY AUTHORITY

The primary wastewater treatment facility for the Greater Pittsburgh area is the Allegheny County Sanitary Authority (ALCOSAN). This facility services 83 communities, including the City of Pittsburgh, and our test location in Monroeville. This 59-acre treatment plant is one of the largest wastewater treatment facilities in the Ohio River valley, processing nearly 250 million gallons of wastewater daily, and servicing a population of 900,000 [18]. Created under the Pennsylvania Municipal Authorities Act, this nonprofit agency is now funded solely by user fees with capital funds raised through the sale of sewer revenue bonds. ALCOSAN recently completed a $400 million capital improvement program focused on odor control, treatment capacity, solids handling, and wet weather planning. Their most recent efforts are supporting one of the largest public works projects totaling $1 billion in engineering and construction projects with the intent of addressing sewer overflows [18].

3. DESIGN METHODOLOGY

The objective of this design section was to produce a plausible Evaporative Roof-spray Technology schematic that may be utilized for prototype testing at the selected test site in Monroeville, featured in this thesis analysis. Therefore, the methodology applied to this project began with the premise of evaluating the amount of rainfall that could be potentially collected or offset from the main storm drain and wastewater collection system by this roof-spray technology. To do this, firstly, the regional climate trends had to be evaluated in order to determine the potential runoff for the test site. After gauging the potential runoff flowrate generated for the site, an evaporation analysis was conducted to find the potential evaporation rate based on the structure's roof surface area. This evaporation rate correlates to the potential volume of rainfall runoff that may be removed from the main sewage collection system. Based on this information, a system was designed to account for the collection, filtration, and storage of this collectable runoff. The sizing of the storage tank, piping system layout, and pump size were all then assessed factoring in the calculated evaporation rate. These components of the design are collected within the Apparatus section of this thesis.

3.1 BUILDING & TEST SITE INFORMATION

This evaluation will focus on the local Monroeville area, including Monroeville, McKeesport, Pittsburgh International Airport, and the Pittsburgh area, as well as focusing on the larger climate divisions to which the local area belongs. These include Pennsylvania's Southwest Plateau and the United States' Northeast climate region.

3.1.1. BUILDING SPECIFICATIONS

The 2.102 acre test site located at 168 Dexter Drive, Monroeville, PA 15668, houses a flooring company and features a large warehouse, storage and fabrication area with an attached business office. The commercial property featured a combination of natural vegetation, tree, and bush foliage as well as an asphalt parking lot roughly half an acre in surface area. Images of the site and diagrams of the warehouse can be seen in Figures 3-1 through 3-7. Figure 3-9 is a blueprint of the property and features warehouse specifications. Currently, infrastructure and asphalt paving covers roughly 40% of the total lot leaving roughly 60% natural. The 12,000sqft steel warehouse consists of a steel, corrugated roof, 150 feet long and 80 feet wide, and a height of 23 ft with a 1/12 slope for the roof-pitch. A layer of insulation within the steel walls was assumed to be 8 in. vinyl-wrap fiberglass. The attached 1,584sqft office is Brick and Mortar, and also has a steel roof. Flooring throughout the entire structure contains radiant heat. The pictures of the building are shown in Figures 3-1 through 3-5. The stormwater systems currently in use include: 2 catch basins that feed off to the right behind the main warehouse into an off-site catch pond, 15" storm drains that connect in to the main regional sewage collection system, and a vegetative swell.

Figure 3-1: Front Right Angled Front View of Main Office and Warehouse

Figure 3-2: Front Left Angled Front View of Main Office and Warehouse

Figure 3-3: Side View of Warehouse Showing Abundance of Natural Vegetation

Figure 3-4: Front View of Warehouse and Main Office from Nearby Hillside

Figure 3-5: Aerial View of Warehouse (Google Earth)

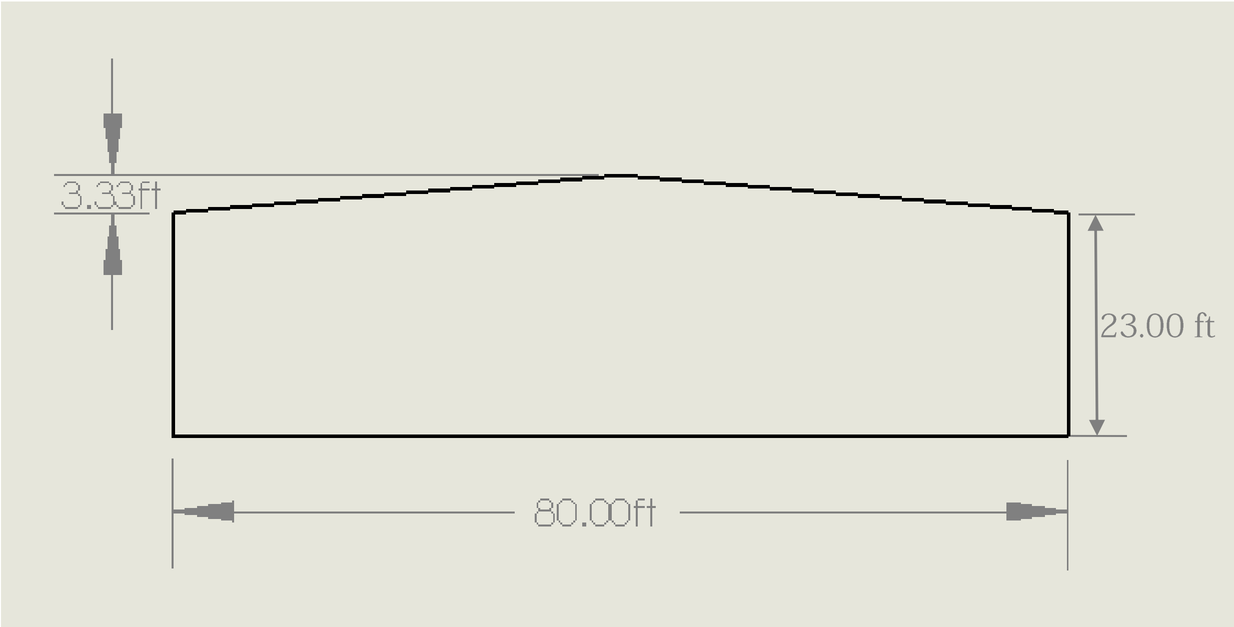


Figure 3-6: CAD Model - Building Width and Pitch Height

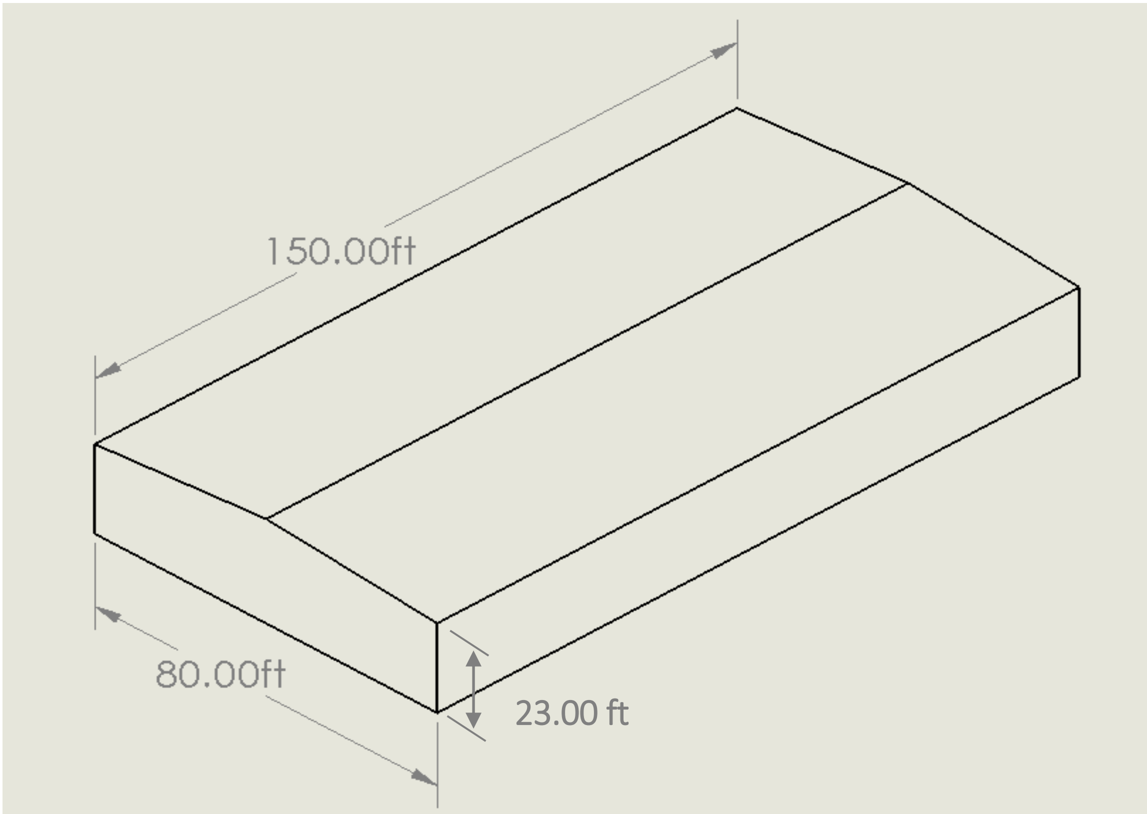


Figure 3-7: CAD - Building Width and Length

The structure's dark grey roof features a corrugated roof design with specification as in Figure 3-8. Note that Figure 3-3 is a general corrugated roof and is cited as an example of the corrugated roof on the warehouse structure. This design element expected to be advantageous for the retrofit evaporative cooling system design. When water is dispersed in sections onto the roof it is assumed that the 8-inch sections will evenly distribute the water for more evaporative cooling potential.

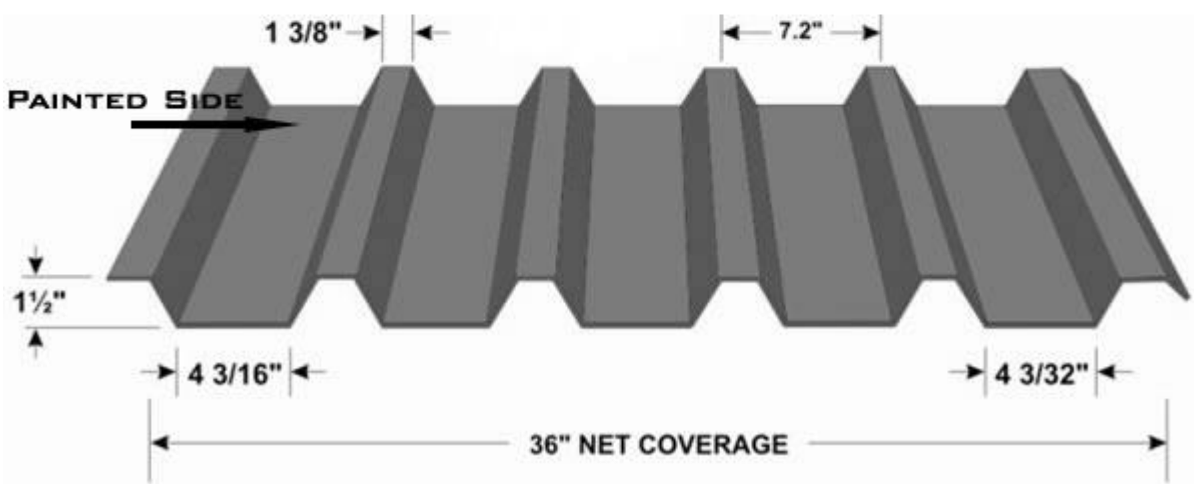
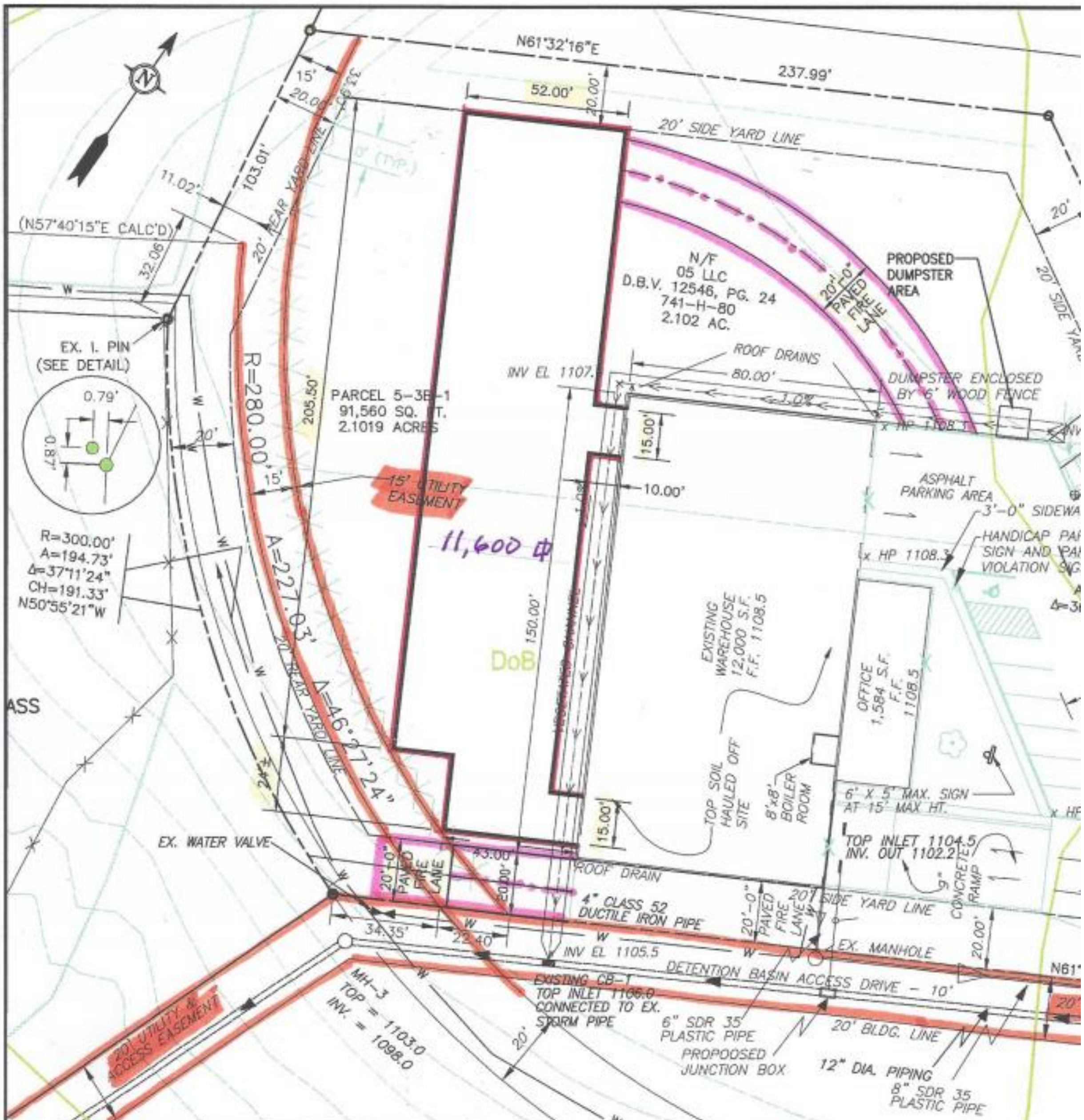


Figure 3-8: Corrugated roof dimensions and example [36]



PARKING SPACE TABLE

CONDITION	AREA (SQ. FT.)	PARKING SPACES			
		REQUIRED		PROVIDED	
		STANDARD	ACCESSIBLE	STANDARD	ACCESSIBLE
EXISTING (WAREHOUSE)	12000	6	–	6	–
OFFICE	1584	6	1	6	1
PROPOSED (WAREHOUSE)	11800	6	–	6	–
TOTAL	1584	18	1	18	1

OFFICE REQUIREMENTS FOR PARKING SPACE: ONE FOR EVERY 250 SQ. FT. OF GROSS FLOOR AREA.
WAREHOUSE REQUIREMENTS FOR PARKING SPACE: ONE FOR EVERY THREE EMPLOYEES OR ONE FOR EVERY 2000 SQ. FT. OF GROSS FLOOR AREA.

SETBACK REQUIREMENTS TABLE

	ALT. 1	ALT. 2	ALT 3
MINIMUM FRONT YARD 40 FT.	✓	✓	✓
MINIMUM SIDE YARD 20 FT.	✓	✓	✓
MINIMUM REAR YARD 20 FT.	✓	✓	✓
MAXIMUM HEIGHT 45 FT.	✓	✓	✓
BUILDING SETBACK 40 FT.	✓	✓	✓

REFERENCE: ORDINANCE 1443, TABLE 201.D, ZONE M-1

Figure 3-9: Warehouse Floorplan Blueprints

3.1.2. CLIMATE AND RAINFALL RATE EVALUATION

The climate evaluation for this thesis analyzed the city of Monroeville, Pennsylvania, located at 40.43°N latitude and 79.77°W longitude. Summer precipitation in Pennsylvania reflects a relatively humid pattern, with average annual precipitation ranging from under 34 inches to more than 60 inches per year. Tropical hurricanes occasionally trail across the state, bringing with them heavy rainfall and flooding. Though precipitation varies by season, it is well distributed throughout the year, with most of the annual volume of rainfall occurring in small storm events of modest size [4].

Given that the National Weather Service does not maintain a weather station in Monroeville, meteorological data trends charted the nearest National Weather Service stations with the most consistent data. This included the McKeesport station, located at 40.35°N latitude and 79.82°W longitude and the Pittsburgh International Airport Station (PIA), located at 40.5°N latitude and 80.26°W longitude. For this analysis, data from both collection centers was utilized. The McKeesport station, being the closest station geographically, was used in the rainfall analysis for the 2014 summer season. The PIA station, which provided precipitation trends from 1981-2010, was selected to simulate the evaporation model presented in this thesis. This was, in part, due to the fact that the McKeesport Meteorological data collection center does not record hourly precipitation trends, which are necessary in understanding the solar trends that are occurring for the potential evaporation evaluation of this system. Comparisons of daily normal temperature data from the two sites can be seen in Figure 3-10, and reveals a correlation coefficient of 1.0 for these temperature trends [45]. This supports the assumption that the temperature trends were consistent between all collection centers for any evaporative and heat transfer evaluations. Additionally, similar elevations between Monroeville and PIA allow confidence that the pressure data extracted from the PIA station will be adequate for the Monroeville model [13].

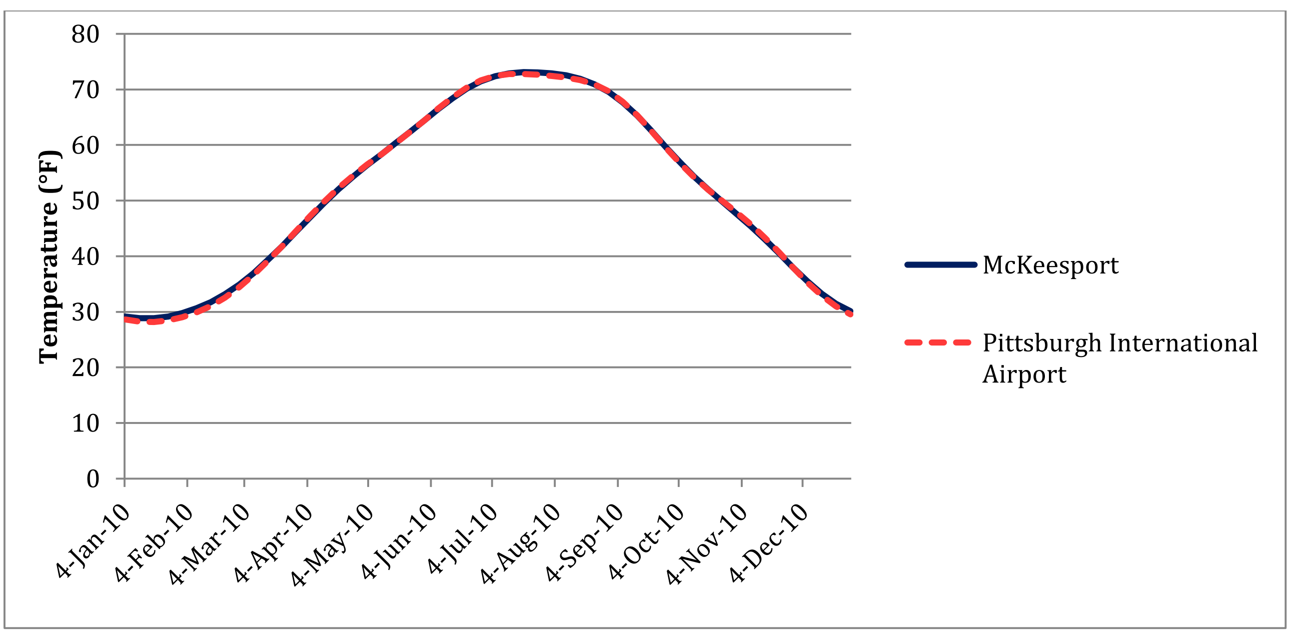


Figure 3-10: Comparison of 30 Year Normal Average Weekly Temperatures, Mckeesport and Pittsburgh International Airport Stations, 1981-2010 [36]

The Evaporative Cooling Roof-spray Systems evaporate water off the hot roof of the building, returning the water to the atmosphere while cooling the interior temperature of the building. Because this system collects water from rainfall and requires higher, summerlike, temperatures to evaporate it back into the atmosphere, it was decided to evaluate the technology for its assumed most useful months, in this case, the summer season. Furthermore, because the analysis and scope of this project is oriented around alleviating stormwater runoff sent to the Allegheny Sanitary Authority treatment plant, this thesis will focus on the summer seasons as define by ALCOSAN as May 1 to October 31 [46]. Therefore the design and associated decisions will all be grounded on the analysis of the system's usefulness during this summer season [15].

In order to analyze the stormwater runoff trends associated with the Monroeville test site, precipitation trends were evaluated for the ALCOSAN summer season (May 1 – October 31) for both the McKeesport and Pittsburgh Airport data sources. It should be noted that, though the 2014 summer season generated increased amounts of precipitation, 21.8 inches more than the 1981-2010 trend, this is acceptable based on the predictions that rainfall is to increase for the region over the next several decades. Furthermore, while the Airport data depicts a trend spanning roughly 30 years, the McKeesport data is the actual rainfall that occurred for the region in 2014.

Rainfall analysis for this study also included the evaluation of recurrence interval storms. Due to the fact that the peak yearly rainfall incidences, or 1-year storms (≥ 2 *inches* for a 24hr period), are an often occurrence that must be handled by regional wastewater treatment facilities; let it be suggested that designs of a rainwater runoff system should at the very least be able to contain or divert a majority of the rainfall incurred from these heavy rainfall events, as a minimum obligation. Furthermore, in order to account for the anticipated increase in annual rainfall of possibly more than 10% for the Pennsylvania region, this system could conceivably be designed to consider rainfall events up to 25-year recurrence intervals (≥ 4 *inches* for a 24hr period), with the addition and proper integration of other evaporative technologies into the system. Figure 2-8 in Section 2.1.4 shows the recurrence intervals for the 1 through 1000-year storms for inches of rainfall with respect to time [3] [33][30]. Therefore, in order to account for, and to analyze a multitude of scenarios, calculations for runoff potential and the peak discharge were conducted for the 1-year and 25-year storms, to provide a solid range from which rainfall loadings could be inferred. The 1-year storm, in addition to occurring annually, was considered in the tank capacity selection and filtration rate components of the apparatus design (Section 3.6 of this report) to account for the expected increase in heavy rainfall [1] [2] [3]. The 25-year storm was selected as an "extreme-scenario" comparison and, in part, due to the life expectancy of this technology spanning 25-years. Calculations for the 25-year storm were primarily used as a comparison marker to determine the potential for the evaporative cooling technology to alleviate the main sewage collection system of collected stormwater runoff, in instances of extreme and sudden rainfall. The resulting peak discharge rainfall from these storms and the average McKeesport precipitation rate were tabulated in Tables A-3 through A-7 in the Runoff Calculations section of Appendix A, and the calculations can be found in Design Section 4.1.

3.2 COMPUTING RUNOFF

3.2.1. METHODOLOGY TO COMPUTE RUNOFF

Due to the unpredictability and variability of the weather and its rainstorms that vary in length and intensity, it was assumed that the most logical analysis of the Monroeville rainfall patterns was to design for scenarios relative to the 1-year recurrence storm and consider the 25-year recurrence storms as an extreme case. An average 1 year storm, for this region, produces 2 inches of rain over 24 hours (0.083 in./hr.) and the 25 year storm produces 4 inches over 24 hours (0.16 in./hr.) [47]. Surfaces capable of generating runoff for our test site include, the metal structure, asphalt paved roads and parking lot, and the natural (undeveloped) earth. In order to determine how much total runoff is generated by the 2 acre test site, all three surfaces had to be accounted for.

3.2.2. RATIONAL METHOD FOR PEAK DISCHARGE RUNOFF CALCULATION

Two procedures were used to calculate the peak and total runoff flowrates for the test site in Monroeville, PA: the Rational Method for Peak Discharge, and the Soil Conservation Service Runoff Curve Number (CN) methods. Because there was little to no percent difference between the two, the Rational Method for Peak Discharge was selected to be utilized for this study, as it was assumed to be the more desired due to its accounting of the location's characteristics, and its simpler approach. Therefore, the Rational Method Peak Discharge equation 1 was used [6]:

$$\boldsymbol{Q_P = CiA} \tag{1}$$

Where,

Q_P is the peak discharge (cfs)
A is the drainage area in (acres)
C is a runoff coefficient based on the ground surface type (0<C<1)
i is the average rainfall intensity in inches per hour (in./hr)

Because the test lot is 2.102 acres, it falls under the "small catchment/drainage area" (x < 200 acres) locality restriction [15]. Where Q_P is the peak discharge, you can calculate the expected peak runoff rate and volumes. A compilation of the calculated Rational Method for Peak Discharge for the various rainfall conditions evaluated can be found in Appendix A: Runoff Calculations.

In order to account for the natural 60% of the test site, the soil composition and slope of the earth had to be considered. The soil composition allows one to determine the infiltration capability of the soil. According to the Penn State College of Agriculture, the Pittsburgh Plateau region, where Monroeville is located, most commonly has silt loam soil [48]. The test site's natural surfaces feature good condition grass and foliage with a 2-7% slope. By knowing the slope of the area, the infiltration rate may be found, where the surface of the ground is the system, the rainfall rate and the infiltration rate sum to a net gain or loss in the water accumulation. A net gain indicates the presence of runoff while a net loss indicates the complete absorption of the rainfall, equation 2 below shows this relationship.

$$\boldsymbol{W_{SoilRunoff} = W_{Rainfall} - W_{Infiltration}} \tag{2}$$

From this determined ground cover, a runoff coefficient is assumed based on those featured in Tables A-1 and A-2, in Appending A, for every surface type. Note that the runoff coefficient changes based on the recurrence storm being evaluated (i.e. a 2-Year Recurrence Interval equates to a 2-Year storm). Typically, runoff coefficients will increase with the intensity of the recurrence storm, alluding to intensity in the amount of rainfall falling with respect to time.

Utilizing the same logic for the roof and parking lot, Tables A-1 and A-2 (Appendix A) were referenced for their assumed runoff coefficients and selected based on the asphalt and metal roof collection surfaces, and the corresponding recurrence storm. The selected coefficients, storm data, and resulting peak discharge flowrates and volumes were tabulated in Tables A-3 and A-4 in the Appedix A.

In order to translate these peak runoff values into collection rates and volumes, a collection coefficient 0.825 was applied to the calculated runoff to represent the amount that could be harvested. Furthermore, a silt loam soil on a percent slope of 0 to 4 allows for the infiltration rate of the ground to reach 0.5 inches per hour. This is much higher than the rainfall of the design storms, therefore it was inferred that the soil runoff would not contribute to the total collectible runoff. Accordingly the total stormwater harvesting potential neglected runoff collection from natural ground surfaces. This is further explained in Section 4.1: Stormwater Harvesting.

For further understanding of the parameters, let the product of iA represent the inflow to the catchment and/or the maximum runoff rate possible, then we can see that the ratio of peak discharge to inflow is equivalent to the runoff coefficient in equation 3 [15]:

$$\boldsymbol{\frac{Q_P}{iA} = \frac{peak\ discharge}{inflow} = C} \qquad \textbf{(3)}$$

Furthermore, some municipalities require accounting for the change in runoff coefficient (C) with respect to the recurrent interval through the utilization of a correction factor (C_f) which is shown in equation 4[6]:

$$\boldsymbol{Q_P = C_f C i A} \qquad \textbf{(4)}$$

Where, C_f varies by recurrence interval, this information is provided based on the regions developments of these correction factors. It was assumed that C_f would be negligible for the Monroeville test site calculations, and therefore was set equal to 1 (no absorption). The results of these calculations can be found in Table 4-1 of Section 4.1 of this thesis.

3.3 EVAPORATION STUDY

Evaporation defines "the process of converting water from its liquid or solid state into water vapor, which mixes with the atmosphere." The rate of evaporation is dictated by the availability of energy contained at the evaporation surface and difference in vapor pressure of liquid and gas and the potential and ease with which water vapor is allowed to diffuse into the atmosphere [7]. Rainwater is absorbed into the soil, grass, trees, natural root system, etc. and provided the appropriate time to be evaporated back into the atmosphere, free of synthetic pollutants. In urbanized environments, this feature is lost due to, not only the lack of abundant vegetation and foliage, but also the increased surface area of impervious surfaces such as metal and concrete buildings, or pavement and roadway. Therefore, the key strategy in this thesis takes on the concept of "returning urbanized environments back to Mother Nature through the simulation of her evaporative strategies," in order to offset stormwater runoff from the main wastewater collection systems. In order to calculate this evaporative potential, though, the temperature of the rooftop was first evaluated.

3.3.1. ROOFTOP TEMPERATURE ANALYSIS

For the analysis presented, a model of the heat transfer through the roof of the building was constructed, from which the rooftop temperature could be determined, based on the environmental conditions and heat drawn from the roof via evaporated water. This analysis was done in time intervals of one hour over the course of a year. The environmental information for each time interval is drawn from the "Typical Meteorological Year" data for the Pittsburgh International Airport. One key assumption made that is fundamental to this analysis is that the thermal system for each time step is in quasi- equilibrium, meaning that, although the environmental and thermal conditions are changing, they are doing so at a rate slow enough (over the course of an hour) that the system can be analyzed as if it were in equilibrium. The second primary assumption was that the ambient temperature was to be a constant at 25°C (77°F, or average summer room temperature for a workspace). This assumption was necessary to fix the internal conditions and be able to solve for the rooftop temperature, which would be difficult to determine without this assumption. The constant internal ambient temperature is analogous to buildings where there is already an active air conditioning system, and means that this analysis is most applicable for determining energy savings for such buildings. Furthermore, to ease the analysis, only natural convection was considered. Finally, the thermal resistance of the film of water on the rooftop surface was also ignored.

In calculating the rooftop temperature, iterative methods is used, where the convection heat transfer from the roof's inside and outside surfaces are based on it. It is helpful to consider the analogy between heat transfer and electricity, where the thermal circuit of the roof can be modeled as follows (Figure 3-11):

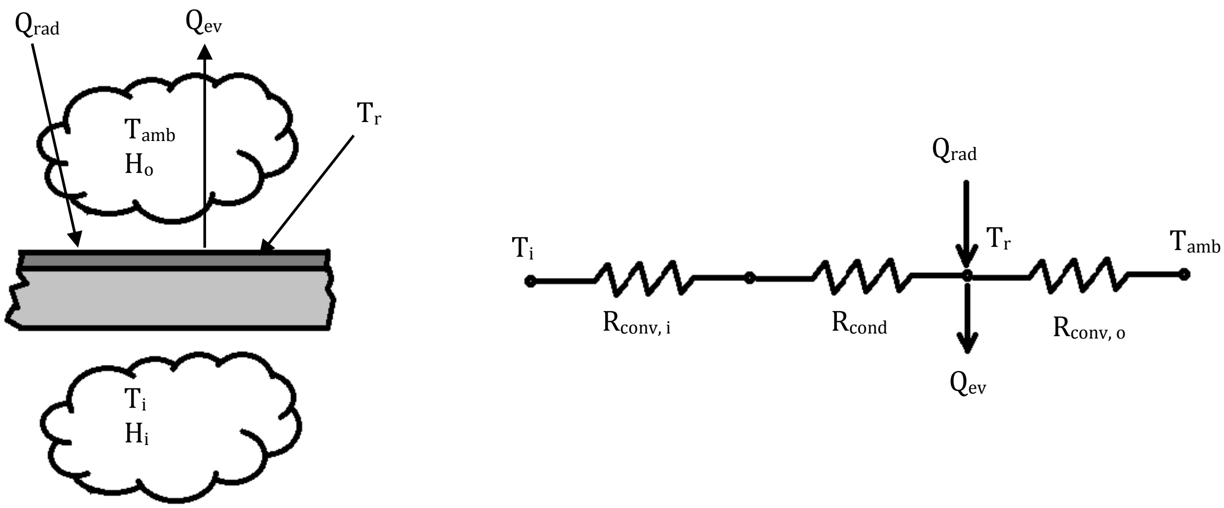


Figure 3-11: Thermal Circuit model of Roof

$R_{conv,\,i}$ and $R_{conv,\,o}$ are convective thermal resistances, and are functions of the temperature of the roof (or ceiling) surfaces and the environmental conditions inside and outside the building.

3.3.2. EVAPORTATION AND THE EVAPORATIVE COOLING POTENTIAL

Although roof-cooling technology has been proven to offset cooling costs, these systems are not a substitute for air conditioning [21]. Their job is to dissipate the substantial heat gained from solar radiation. Therefore, one must understand that their design is oriented around exterior latent heat loads, not internal loads. This means that these technologies will be more effective with a larger roof area in proportion to exterior walls [23]. Therefore, when designing the Evaporative Roof Cooling Systems (ERCS) the strategy is "not how much water you can apply, rather, how much water you can evaporate" [23]. Too much water on the roof diminishes cooling potential. In addition, uniform distribution of water sprayed onto the roof is essential [23] [13]. To model the evaporation and cooling process of water on roofing, several components such as solar energy (Q), temperature (T), and thickness (δ) need to be analyzed [21] [13].

3.3.3. EVAPORATION RATE CALCULATIONS

The primary return for the Evaporative Roof-Spray Technology, in this study, is its ability to remove excess runoff from overloading the main sewage collection system, making the technologies ability to cool interior spaces an added benefit. The evaporation of a fluid from a surface is a function of the atmospheric conditions including humidity, temperature, the magnitude of solar radiation, and the temperature of the roof. With the energy being transferred by the evaporating water, heat transferred through the roof into the building is decreased, reducing the rate at which the interior temperature rises. As the relative humidity (RH) of an area increases, however, the effects of evaporative cooling on a roof are reduced due to a slowed rate in evaporation.

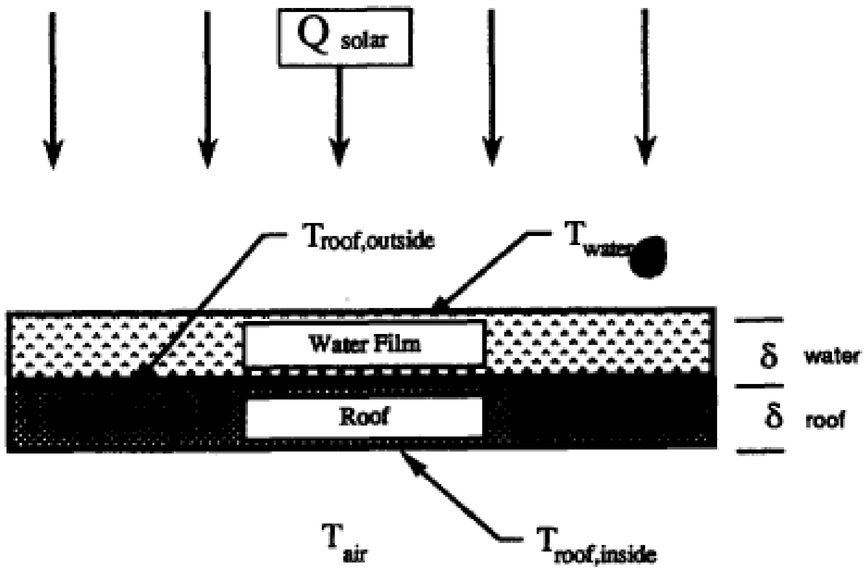


Figure 3-12: Represents the variables considered when investigating the temperature of roofing when a water film is present [21].

In Figure 3-12 Q_{solar} is solar energy, $T_{roof,outside}$ is the outside roof temperature, $T_{roof,inside}$ is the inside roof temperature, T_{water} is the water temperature, T_{air} is the air temperature, δ_{watar} is the water film thickness, and δ_{roof} is the roof thickness. A variation of water film thickness produces change in the film's thermal resistance. Changing the thickness of the liquid layer produces a very small effect on the surface temperature of the water film. This small change allows for the assumption that variation in water film depth does not prompt a prominent thermal effect on the overall system [21] [13].

To find the mass flow rate of energy due to evaporation, more precise factors need be introduced into the system, i.e. the wind speed factor (θ), the relevant surface area of what's being observed (A), and the pressure factors relating the saturation pressure at the water surface (X_s) to the ambient pressure and humidity levels (X) [21] [13]. This information, in combination with the calculated rooftop temperatures, all effect the amount of water evaporated from the roof surface, so this iterative process also yields the mass of water evaporated and heat drawn from the roof through evaporation. The evaporation model to calculate Q_{ev} used in this analysis was built upon equations 5-11 [49]:

$$P_{ws} = \frac{e^{77.345+0.0067*T_{atm}-\frac{7235}{T_{atm}}}}{{T_{atm}}^{8.2}} \tag{5}$$

$$P_w = RH * P_{ws} \tag{6}$$

$$X_s = \frac{0.62389 * P_{ws}}{(P_{atm} - P_{ws})} \tag{7}$$

$$X = \frac{0.62389 * P_w}{(P_{atm} - P_w)} \tag{8}$$

$$\theta = 25 + 19 * S_{wind} \tag{9}$$

$$Q_{ev} = h_{fg} * \theta * A * (X_s - X) \tag{10}$$

$$m_{ev} = \theta * A * (X_s - X) \tag{11}$$

Where:

P_{ws}	is the surface pressure (lb_f / ft^2)
P_w	is the surface pressure (lb_f / ft^2)
T_{atm}	is the dry bulb atmospheric temperature (Kelvin).
RH	is the atmospheric relative humidity (%).
S_{wind}	is the wind speed (m/s).
h_{fg}	is the heat of vaporization for water at the film temperature, 0.5(T_{roof} + T_{inf}) in kJ/kg.
A	is the rooftop area (m^2).
Q_{ev}	is the energy absorbed by the water via evaporation (kJ).
m_{ev}	is the mass (flowrate) of water evaporated (kg/hr).

This model calculates the amount of water that could be evaporated if water was always available for the system. Therefore, the only restrictions in calculating the maximum evaporation rate concern when sunlight is available to cause evaporation. Assuming a possible 12 hour evaporation period, daily, for the duration of the 183 day summer season (May 1-October 31), and a maximum evaporation rate of 23 gpm this system, when applied to the test structure's roof, can potentially evaporate as much as 3,030,500 gallons of water. Unfortunately this amount of evaporation is unlikely in reality because it would be impractical for a system to economically be to supply enough water to reach this potential. In addition, changes in availability of sunlight will likely reduce the amount of evaporation potential to less than the assumed 12 hours, daily. Furthermore, even if they were not limited by the amount of rainfall, the size of collection and storage tank utilities would prove unreasonable for private-installment applications. A more realistic amount of water that one could expect to evaporate over the course of the entire summer season is calculated using the average evaporation rate of 2.84 gpm. Using this rate produces a total volume of 374,200 gallons evaporated for the summer, which also more properly accounts for an assumed 10,000 gallon tank (see sections 3.6.3 and 4.3 for more details on the storage design selection).

The maximum and average evaporable volume values were generated using the calculated evaporation rates of 23 gpm and 2.84 gpm, which were acquired through the utilization of equations 5-11. Equation 11 produces the mass of water evaporated over the course of 1 hours' time, therefore this provided the maximum and average evaporation rates in terms of kg/hr, which was then converted into gallons per minute. In order to achieve these rates, firstly, several environmental and site specific information variables were established regarding temperatures, rainfall, evaporation, and geometry of the building. This included establishing the following meteorological information:

P_{ws}	4.9889x10^3 lb_f / ft^2
P_w	1.5965x10^3 lb_f / ft^2
T_{atm}	27.8 °C
RH	32%
S_{wind}	10.3 m/s
h_{fg}	2446.6 kJ/kg
A	1.0255x10^3 m^2 (effective) or 1.0219x10^3 m^2 (actual)

Which resulted in the following maximum evaporation conditions:

Q_{ev}	1.2795x10^7 kJ/hr
m_{ev}	5229.7 kg for 1 hour or 23 gallons per minute

In order to obtain the average the continuously changing temperatures involved had to be accounted for, therefore, these variables all became dependent on the time step involved in the iterative process. The meteorological data from the Pittsburgh Airport center was entered for the various climate variables. The key variable in the evaporation calculations concerned the thermal resistance (Tr) which was iterated for every time step, at every hour, of every day of the summer season. This, once converted, produced the average evaporation rate of 2.84 gpm which accounted for the temperature variations resulting from the imported climate data.

3.3.4. EVAPORATIVE COOLING POTENTIAL

From the evaporative cooling rate calculated for the rooftop surface (Q_{ev}) the amount of cooling witnessed by the interior of the building can also be determined. This calculation was performed by transforming the thermal circuit used in the first part of the analysis into an equivalent circuit where all the thermal resistances, node temperatures, and the radiation heat transfer are the same, but Q_{ev} is removed and replaced by Q_{cool} on the inside ceiling surface of the building. Figure 3-13 illustrates this rearranged circuit and the corresponding variables.

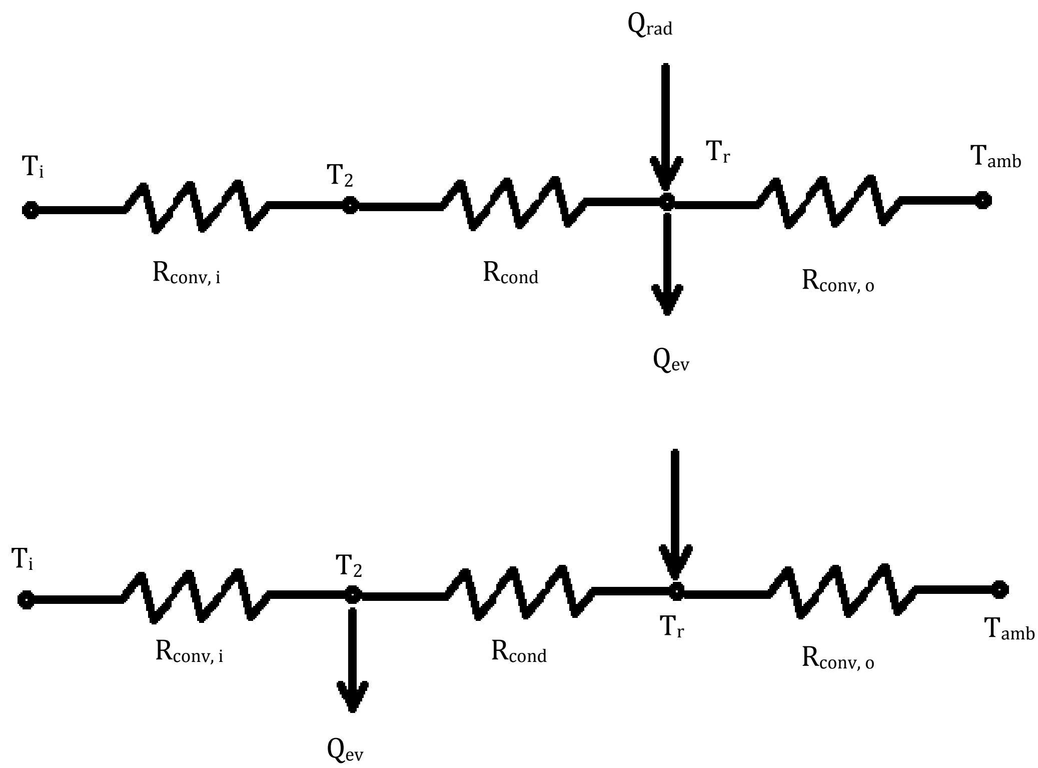


Figure 3-13: Equivalent Thermal Circuits

Performing this conversion yields an amount of heat transfer from the building (in Btu's), which is analogous to an amount of air cooling within the building. The Energy Efficiency Ratio (EER) is utilized in the evaluation of an air conditioning system to evaluate the ratio of cooling provided over the electrical energy consumed (equation 12), this allows for the measurement of performance for air conditioners to be utilized in thermal calculations of efficiency for power cycles [16]. Using equation 12 in relationship with Figure 3-13, one is able to calculate the maximum, minimum, average and total energy that can be extracted from the building.

$$Q_{cooling} = \frac{T_1 - T_2}{R_1} + \frac{T_4 - T_3}{R_3} - Q_{ev} + Q_{rad} \tag{12}$$

Where,

Q_{ev}	is the energy absorbed by the water via evaporation (kJ)
Q_{rad}	is the radiative heat transfer rate (kJ)
$Q_{cooling}$	is the heat extraction or cooling effect (kJ)
T_1, T_2, T_3, T_4	Temperatures within the circuit analysis (K)
R_1, R_2	Resistances within the circuit analysis (K/kJ)

Using Equation 12, the maximum potential heat extraction was found to be 982,168 Btu/hr, and the average for the summer is 93,516 Btu/hr. Table E-1 in Appendix E provides a compilation of the found energy values for the system daily over the course of the summer season. Using this average, the standard deviation of the tabulated energy extraction values, and a 95% confidence interval, generated a range of potential energy absorption by the system. A 95% confidence interval requires the adding or subtracting of two standard deviations of the data set. Completing this calculation results in a potential energy of heat extraction range from which the total heat extraction for the summer season can be interpreted. Therefore the minimum heat expected heat extraction is 69,706 Btu/hr, whereas the maximum potential cooling energy is 117,326 Btu/hr.

Many who design and evaluate air conditioning systems have grown accustomed to utilizing the Energy Efficiency Ratio (EER) when assessing AC systems for their efficiency and energy usage. An air conditioners EER is the ratio of the cooling capacity to the power input, which can be seen in equation 13. The higher the EER rating, the less likely there will be a payoff in cooling. An accepted EER air conditioning rating of 7 was selected for this evaluation and can be see utilized in the evaluation of the equivalent cooling value in the tank capacity analysis (reference section 3.6.3 and Table B-1 Appendix B) [50]. Applying this value to the calculated energy extraction values results in providing the potential monetary value for a return on investment through the cooling effects of the spray roof system.

$$EER = \frac{Cooling\ Capacity\ (Btu/hr)}{Power\ Input\ (Btu/hr)} \tag{13}$$

To assign a monetary value to this cooling potential, an electrical energy cost of $0.08 per kW-hr was used. Using this assumed (conservative) coefficient and energy cost value, various cost-related evaluations were able to be conducted regarding the storage tank, feasibility analysis, and potential for energy savings. The standard running time for Pittsburgh PA air conditioning systems for the summer season is 737 peak load hours. This value is based on the generally accepted full load cooling hour's data collected by Total Performance Diagnostics [51]. Applying these assumptions to the average energy extraction yields the following sample calculation for electrical payoff:

$$93{,}516\frac{Btu}{hr} * \left(\frac{1\ Ton\ AC}{12{,}000\ Btu}\right) = 7.793\ Tons\ AC$$

$$(7.793\ \ Tons) * \left(746\frac{W}{Tons}\right) * \left(\frac{1\ kW}{1000\ W}\right) = \ 5.816\ kW$$

$$(5.816\ kW) * (737hrs) = 4284.61\ kW\ accounting\ for\ AC\ running\ time$$

$$(4284.61\ kW) * \left(\frac{\$0.08}{kW}\right) = \$\ \boldsymbol{342.77\ savings\ for\ the\ summer\ season}$$

3.4 PRODUCTIVITY VS. TEMPERATURE

Studies have shown that there is a worker performance increase with temperatures from around and up to 21-22°C (69.8-71.6°F), as well as performance decreases with temperatures exceeding that of 23-24°C (73.4-75.2°F). This allows for the conclusion to be made that the negative effect on working performance temperature ranges from the 21-24°C (69.8-75.2°F) realm [52].

Figure 3-14 below shows the relationship of the temperature versus the percentage change in performance, and Figure 3-15 below gives an idea to what the temperature is that yields the maximum normalized performance (where 1 = 100%) and the relative performance degrading at temperatures above and below [52].

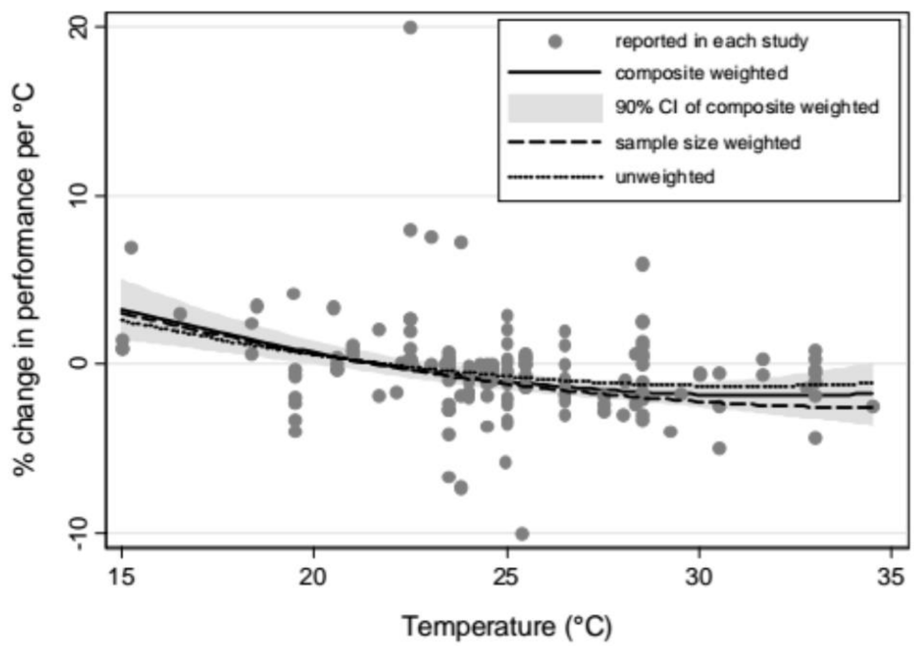


Figure 3-14: Percent Performance Change vs. Temperature [45]

There are currently no regulations currently in place that specify a range of appropriate working temperatures inside a workplace established by the Occupational Safety and Health Administration (OSHA). However, OSHA does promote an acceptable or "healthy" working range of 68°F -76°F with a humidity of 20%-60% [53]. Studies have also shown that the optimal temperature range for working coincide with this recommended range suggesting 21-24°C (69.8-75.2°F) [52] [13]. Figure 3-15, below, demonstrates the relationship between performance and temperature. Therefore, it is believed that there is the potential to increase and optimize productivity through the implementation of spray-roof evaporative cooling technology.

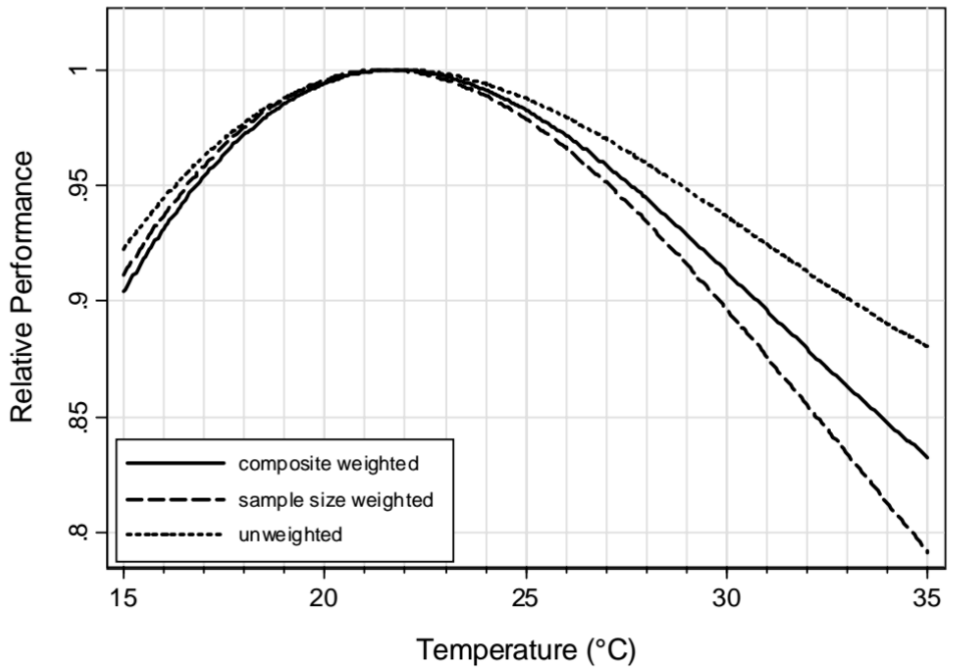


Figure 3-15: Performance vs Temperature [52]

3.5 LEED BENEFITS

There is the potential for government tax reprieves and benefits when implementing environmentally conscious technologies. More specifically, these assistances may come in the form of LEED credits. Leadership in Energy & Environmental Design (LEED), is a green building certification program that "recognizes best-in-class building strategies and practices" [54] . The selected tank in the apparatus design of this thesis was picked with the intent of drawing from these potential remunerations. "Owners and designers of new construction and major renovation projects can use Xerxes fiberglass products and qualify for points under the U.S. Green Building Council's sustainable sites and water efficiency categories of its Leadership in Energy and Environmental Design (LEED®)(1) Green Building Rating System™" [55]. Four potential categories of LEED Credit that the owner could qualify for include:

- LEED Credit for Stormwater Design (Credit 6.1 / 6.2)
- LEED Credit for Water Use Reduction (Credit 3.1 / 3.2)
- LEED Credit for Innovative Wastewater Technologies (Credit 2)
- LEED Credit for Water Efficient Landscaping (Credit 1.1 / 1.2)

Achieving the credits mentioned above contributes points to help a building become LEED Certified. For building owners, LEED Certification could provide their business with a competitive differentiator, attract tenants and/or increase rental rates, improve public and community relations, and lower operating costs. 61% of corporate leaders believe that sustainability leads to market differentiation and improved financial performance. "In a recent Nielsen global survey on corporate social responsibility, more than half (55%) said they are willing to pay extra for products and services produced or offered from companies that are committed to positive social and environmental impact" [56].

3.6 APPARATUS

This section methodically outlines the design procedure followed to layout and size the various equipment and utility components of the spray roof apparatus. Following in order from collection to evaporation, this section will first address (1) how the stormwater is to be collected, followed by (2) the filtration selection, (3) storage tank sizing, (4) piping design and layout, and, lastly, the (5) sizing of the pump.

3.6.1. STORMWATER HARVESTING

By categorizing the test site into permeable and impermeable surfaces, a strategy was derived to address the varying surface types of the test site and determine what would be collected and through what means. For this specific application, three surface types have were identified that must be addressed uniquely. These consist of the roof of the test structure; the parking lot and any other paved surfaces, roadways, or sidewalks; and the undeveloped ground, which accounts for the remaining 60% of undisturbed area of the site. Table 3-1 outlines the surface area of the various surface types for the test site. In order to harness this stormwater runoff through collection, treatment, storage, and evaporative systems, the current site must be altered for effective harvesting schemes. The collection of rainwater from the roof and pavement requires modification of the current roof gutter and downspout system, as well as the installation of a pavement runoff collection system. Currently, water is channeled by these surfaces to a detention basin or is rerouted directly into the main sewage collection system. After applying the corrective retrofits, it is assumed that the roof-spray technology will be able to utilize water collected from the parking lot and main structure.

Table 3-1: Surface Analysis of the Test Site [39]

	Surface Area [ft^2]
Total Lot	91,563
Total Infrastructure Area (before expansion)	36,625
Warehouse	12,000
Office	1,584
Parking Lot	23,041
Natural Ground	54,938

Though the total runoff was calculated in Section3.2 in order to determine the total runoff currently collected by the main sewage collection system, for this design it was deemed appropriate to only harvest stormwater runoff from the structure and parking lot. Though the goal of this technology is to prevent stormwater runoff from reaching the regional wastewater treatment plant, with financial restrictions on the size of the storage tank, this limits the potential rainwater harvesting that the system can implement. Furthermore, not only is the average amount of groundwater runoff primarily absorbed by the silt-loam soil surface (See Section 3.2.2.), but it would also become highly unsuccessful financially to attempt to filter, store, and redirect this larger amount of collected water. Another primary concern of these evaporative technologies is the desire to keep polluted waters from entering the natural environment. For this component of the evaluation it was assumed that rainwater in the natural sections of the property would be free of synthetic pollutants. In addition, the Monroeville test site currently has a natural collection pond on site; this pond could be utilized to collect any excess groundwater runoff. If implemented in other locations, other evaporative technologies could be integrated into the system in order to also address issues associated with runoff from the underdeveloped land or tank overflows at peak rainfall hours.

A two part collection method, oriented around the two collection points on the test site, was proposed to capture all of the runoff from the site's structure and paved surfaces. The first collection source will be from the site's paved surfaces, primarily the 0.53 acre parking lot. Fortunately, the paved lot, due to common construction practice, has been designed with an intended slope to direct the water towards a grassy hillside towards the center of the property where an underground channel guides water around the backside of the warehouse to the main sewage collection system. Figure 3-16 shows the location of the current downspouts denoted by red dots and the pavement water flow is denoted by the blue arrows. The proposed system to collect pavement runoff will take advantage of these design parameters currently in place. The approach is to apply a "flow-through system" located above the current collection channel. Flow-through systems are filled with gravel, soil, and vegetation, and are commonly designed to be waterproof [57]. According to the site map in Figure 3-17 [47], the length of the pavement collection region is 60 feet. Flow-through systems are similar to a bioswale in that they direct runoff to a drainage pipe to disperse water. However, they differ in that this design utilizes a layer of gravel, allowing a greater volume to settle around the drainage pipe to direct water to a specific location more quickly, which for this system would lead to the main collection tank. Flow-through system planters are capable of reducing "stormwater flowrates, volume, temperature, and improve water quality" [57]. Furthermore, not only are flow-through filters adaptable for any range of site size, they are also able to be constructed next to building foundations (where infiltration is a concern) and are suitable for all soil types [57]. An example construction of the pavement system may be seen described in Figure 3-18, which also features the option to integrate downspout collection. Note that a growing medium (optional) featured in the figure demonstrates the potential to encourage intentional planting of natural vegetation agents that may work to assist in the handling and removal of stormwater runoff from the primary collection system. For this flow-through system, the vegetative medium acts as an overflow catch, filtering sediment and pollutants as the water infiltrates through the designed planter, and absorbing excess runoff during peak rainfall occurrences, and is esthetically pleasing to the eye [57].

Figure 3-16: Modified Downspout Locations for Retrofit Rainfall Collection System [47]

Figure 3-17: Location and Direction of Existing Parking Lot Drain Channel to be Modified [47]

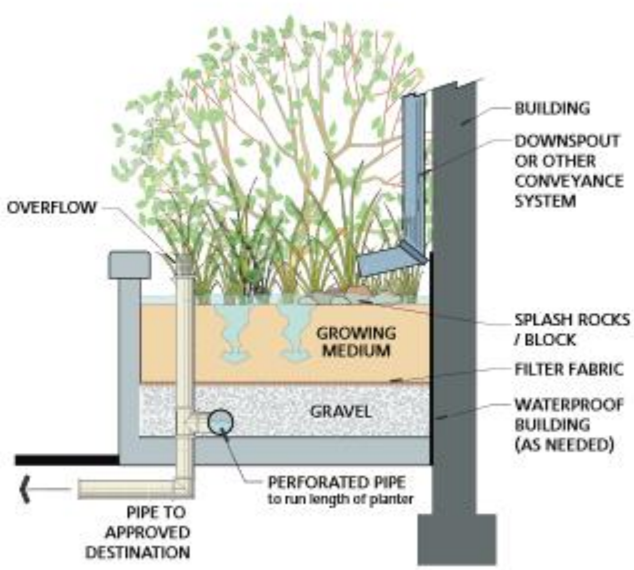


Figure 3-18: Example Diagram of Flow-Through System [57]

The second collection component focuses on collecting from the structure itself and taps into the main gutter collection system. The test site is currently equipped with a gutter system along the entire length of the warehouse as well as each edge of the office. Seven downspouts line each corner of the warehouse and two corners of the office (denoted by the red dots in Figure 3-16). These gutters direct rain runoff to each corner of the roof; inevitably causing half of the water from the roof to travel towards where the storage unit will be located, and the other half in the opposite direction. While it would be ideal for all water that contacts the roof to flow in the same direction towards a single collection point, a complete renovation of the gutter system, and relocation of current downspouts, must take place in order to achieve this. Because a complete renovation of the current gutter system is financially expensive, an alternative design is outlined in this thesis.

The retrofit roof design utilizes the current gutter system's strategy of collecting water through all four corners of the roof and then links into two primary piping and downspout collection routes that direct all runoff towards the selected storage location on the North West side of the structure. One path directs half of the collectible water from the warehouse roof, via the existing gutter system by way of the downspouts that run in the direction of the spray roof collection piping systems and storage unit. In the case of an underground storage unit, the two spouts will connect to a channeling pipe directly to the unit below surface of the earth.

In order to acquire the water directed away from the collection tank, a second path must be created. The strategy is to divert this runoff into the parking lot collection system via a series of altered downspouts, without allowing the water to be contaminated by waste and chemicals on the parking lot surface. While this method seem non-ideal, alteration of the current locations of the downspouts of the office and warehouse would require costly and irrational construction efforts such as running piping across entry ways, digging up pavement, or running piping along walls that will be removed with the site's planned building expansion. As a result, the most noninvasive approach is to disconnect the office and warehouse downspouts and allow roof water to divert to the parking lot. Downspout disconnection has proven to be an effective way to keep runoff local by cutting the connection from the downspout to the sewer drain [58]. Consider the modified downspouts in Figure 3-19, the blue dots represent the downspouts that will be modified to direct water via the parking lot flow-through collection system [47]. The current downspouts are to be cut at the bottom and directed around the corner of warehouse so that it may feed directly to the collection system leading to the main storage tank (see Figure 3-20). This will require two 5in. by 6in. 90-degree elbows and a 6in. by 5in. 90-degree elbow. At the bottom of the downspout, a length equal to the height of the elbow assembly (12.5 inches) will be removed and attach to the bottom of the final elbow section. The assembly will be mirrored from both sides of the facility at the downspouts.

Figure 3-19: Modified Downspouts that Connect to the Pavement Collection System [47]

When designing downspouts, the appropriate number of downspouts corresponds to a ratio of square footage of the roof to square inch of the downspout as 100 to 1 [59]. With the facility spanning a surface are of 13,500 sq ft, not accounting for the roof pitch, the area of downspout drainage must cover at least 135 in.^{2} [47]. The proper sizing for the downspouts should be designed with a cross-section of 6in. x 5in, requiring that a minimum of 5 downspouts be integrated into the system. Two of these downspouts will service the roof collection route that feeds directly to the storage collection pipeline on the recommended north-west side of the structure. The other three downspouts will be modified to send water through the parking lot collection system.

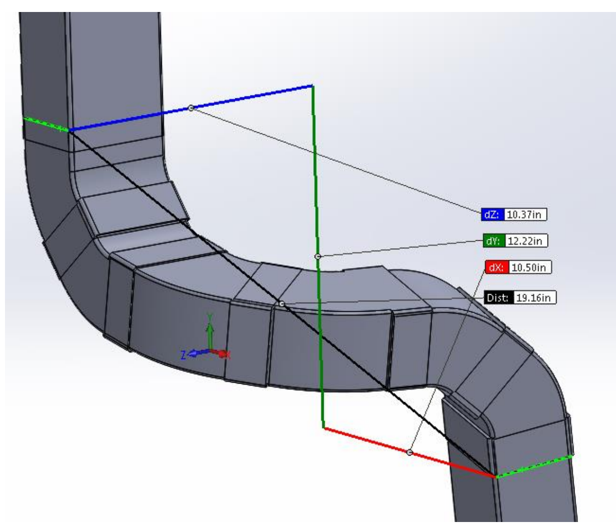


Figure 3-20: Sample Modified Downspout with Re-Routing Assembly

3.6.2. FILTRATION

The collection and storage of stormwater is highly dependent on the system's ability to filter out dangerous toxins and debris in order to prolong the life and usefulness of the water when sitting in the tank. Proper filtration systems clarify collected water in order from the larges particles to the most fine particle size desired and takes into account the desired final quality of filtration. Because spray-roof technology doesn't require "drinking water" quality, "greywater" was deemed acceptable for this application. There are no quantitative standards to define greywater; however, greywater can roughly be defined as "water that has not come in contact with feces or harmful toxins, but still contains traces of dirt, food, grease, hair, and certain household cleaning products" [60]. This lightly soiled water will not spread dangerous germs or bacteria and can safely be sprayed onto a roof and evaporated. The key in selecting the filtration for this design it to keep collected greywater from deteriorating to the "black water" rating, at which time it is no longer usable in the spray-roof system. If further treatment is desired, installments of economical chemical feed systems, such as "Biocide" can be integrated with the pump system to maintain proper pH balance, preventing the risk of algae growth on the roof.

The degree of filtration, or "fineness," of particles is measured in microns. Properties containing more organic material such as trees, plants, animals, etc. require finer filtration to remove bacterial and decomposable matter. Systems will also be size dependent, requiring a larger system for bigger collection applications. The filtration system selected for the warehouse in question was an in-ground filter with a 254 microns standard, which will satisfy the 250 micron criteria. This will remove any large debris material before the water enters the tank, where it would disrupt the pump and spraying system. Furthermore, organic material will be removed in order to prevent decomposition and degradation of the water.

Filtration rates vary based on the filtration systems selected and their intended purpose. Because the spray-roof technology requires the ability to filter harvested water at a faster pace, slow filters are impractical for such an application. Therefore, the filtration system ultimately chosen will be unique to the application with the size dependent on the amount of water being captured and the degree of filtration quality will be specific to the Monroeville environment in order to effectively filter out polluting materials picked up by the collected rainwater.

To address the needs of the Monroeville Spray Roof System, the filter must be capable of processing runoff, at minimum, from a 1 year recurrence storm. It must be capable of handling the average flow rate of water collected during such a storm. In Monroeville, the rainfall of a 1 year recurrence storm over a 24 hour period is 2 inches [61]. Taking into consideration the area of the buildings and pavement on the site, it is calculated that the average flow rate of a 1 year recurrence storm is 0.53 gallons per second. Therefore, the system will feature an industrial grade mesh filter, with manufacturer specifications outlined in Table 3-2 and diagramed in Figure 3-21, that is able to handle up to 10.7 gallons per second of water [62]. This is more than enough to accommodate the site for the average 1 year storm.

Table 3-2: Filter Specifications [62]

Price	Max Flow Rate	Connections	Weight	Filtration	Installation Depth
$1,579.95	10.7 Gal/Sec	6" or 8"	80 lb	0.01 In (254 micron)	31 – 59 in

Figure 3-21: In-Ground Filter [62]

The system is self-cleaning and features an above ground lid that allows for easy access to the filter [62]. The designed system also utilizes two overflow points. The first overflow outlet will be between the filter and tank and will allow the system to properly offset any excess water to the nearby on-site collection pond, or other natural outlet, when the tank is full. The second overflow, located just before the filter, will allow the system to bypass the filtration system for the few instances where the flow rate of collection may exceed that of the filter, though this result is highly unlikely due to the high flow rate capacity of the selected filter. It is also possible to integrate other filtration technologies into the design; therefore, other notable filtration techniques optional to this report are contained in Appendix C.

3.6.3. STORAGE

A water storage tank will be used to store the collected rainwater until it can be returned to the atmosphere via evaporative or other environmental water-conservation technologies. Several of the main factors that should be considered when selecting the appropriate tank include whether the tank will be installed above or below ground, tank material composition, and, most importantly, the tank capacity. Furthermore, when determining the tank capacity, consumers installing this system should consider both the environmental benefits and the financial investment in order to determine their desired investment and impact on the environment.

There are advantages and disadvantages associated with installing the collection tank above or below ground. Table 3-3, below highlights some key points the consumer must consider when deciding which option is best for their desired applications. For the warehouse structure in Monroeville, it was assumed that the owners would value above ground space for their current plants to increase the size of their warehouse. Although there are higher costs associated with burying the tank, such as those associated with excavation and foundation anchoring, it is assumed that this would be the company's preference. It was decided that the design would account for a tank that will be buried underground below the maximum frost layer at a depth of 2.5 ft [63].

Table 3-3: Advantages and Disadvantages of Above vs. Below Ground Water Storage Tanks [64]

	Advantages	**Disadvantages**
Above Ground	• Easy to install and takes less time if bought off-the-shelf • Easy to inspect • Ground level contaminants cannot enter the tank	• Poor aesthetics • Space taken up by the tank cannot be used for any other purpose • Tank and cover can be easily damaged (inclement weather)
Below Ground	• Aesthetics • Space above the tank can be utilized for other purposes • Sheltered from episodes of inclement weather • Most suited for large volume storage tanks (x >=10,000L) • Potential to store thermal energy during colder months (below frost-layer)	• Construction is time consuming and incurs excavation and foundation anchoring costs • More prone to contamination • Heavy vehicles may be restricted from being driven over the tank, since the exerted pressures can cause damage

Next, one must evaluate what material strength your system's water tank requires. Storage tanks are available in a variety of materials including polyethylene, precast concrete, metal, and fiberglass. In many cases, larger polyethylene tanks do not have the structural integrity to withstand being buried; and the primary issues associated with metal water tanks is that they are prone to corrosion; furthermore, precast concrete tanks commonly experience deterioration and cracking. Therefore, for this design a fiberglass tank was selected. Fiberglass tanks are corrosion resistant, lightweight, and structurally solid, with a more favorable capacity to strength ratio, making them satisfactory for the scope of this project in allowing the system to store more water.

Finally, a critical factor in designing this stormwater evaporation system is selecting the appropriate capacity storage tank. Under-designing the capacity of the storage tank will lead to the system not performing as desired, reducing the benefit to the environment and the business owner. Over-designing the capacity can lead to both wasted space and an uneconomical investment, yielding little to no return for the investor. In order to properly determine the size of this tank, both the environmental and economical components must be weighed into consideration so that the final tank capacity satisfies needs of the client for their unique site. From an environmental standpoint, the preferred tank capacity would be able to collect all the water that falls on the site. In essence, by collecting all of the water that would otherwise flow into the storm water drainage, the system would act to eliminate the sites contribution to the problem of excessive stormwater entering the primary sewage treatment system.

For the Monroeville sample site, based on the property owner's request, a 10,000 Gallon, Xerxes fiberglass tank was selected. The supplier outlines that suitable applications include rainwater harvesting, chiller unit condensation collection, grey water recycling systems, and stormwater retention. The tank is available for $24,027.70 [55]. Due to the longevity of these tanks, it is expected that this tank will outlast the expected life span of this system, making it a more successful long-term investment. An example of this tank is featured Figure 3-22, note that the image is a general picture used to illustrate the design of the line of Xerxes fiberglass tanks. The specific dimensions of the 10,000-gallon tank can be found in Table 3-4. It should also be noted that more cost-effective alternatives, such as low-end conventional septic tanks, will only cost roughly $2,000-$5,000, and enhanced engineered alternative septic systems that work better than the conventional approach for sites with high groundwater or slowly/rapidly percolating soil, or near drinking water supplies span $10,000-$20,000 [65].

Due to the capricious nature of predicting storm trends, and the lack of economic return from electrical savings, it was assumed that sizing the tank for a capacity relatable to the 1-year recurrence storm, with particular consideration of the size and cost of the tank is deemed a more concrete approach and justification for selecting the tank, as well as the decision of the test site property owner. The capacity evaluation of the selected 10,000 gallon tank can be found in section 4.3.1, and the financial assessment for this tank is outlined in Section 4.3.2. The specifications for this tank can be found in Table 3-4, and is featured in Figure 3-22 [55].

Table 3-4: 10,000 Gallon Tank Specifications [55]

Nominal Tank Diameter (Ft.)	Nominal Tank Capacity (Gal.)	Actual Tank Diameter (Ft./In.)	Actual Tank Length (Ft./In.)	Nominal Tank Weight (Lb.)	Tank Cost ($)
8	10,000	8'-0"	31'-6 1/2"	3,000	$24,027.70

Figure 3-22: Xerxes Fiberglass Water Tank [55]

3.6.4. PIPING DESIGN

The design of the piping system began with understanding the basic flow rate, velocity, and pressure losses that must be accounted for, in combination with laying out the proposed system, and then followed by determining the optimal configuration and pipe sizing in order to transport collected stormwater onto the structure's rooftop. Schedule 80 PVC plastic pipe was selected for the design, but if it is desired to reduce the cost of installation Schedule 40 PVC would also be acceptable [66].

It was assumed that the pump and piping system would have to produce no more than the calculated maximum evaporation flow rate of 23 GPM. This value may also be referenced through the code. Based on the desired pipe diameter and required flow rate, a maximum velocity of 4 ft/sec was established so as to produce no noise pollution. Likewise, the design never allowed for the velocity to drop below 2 ft/sec insuring that trapped air would be carried with the water and not clog the system. The plot in Figure 3-23 from the 2005 ASHRAE Handbook was then utilized to design the desired pipe size and relative head loss.

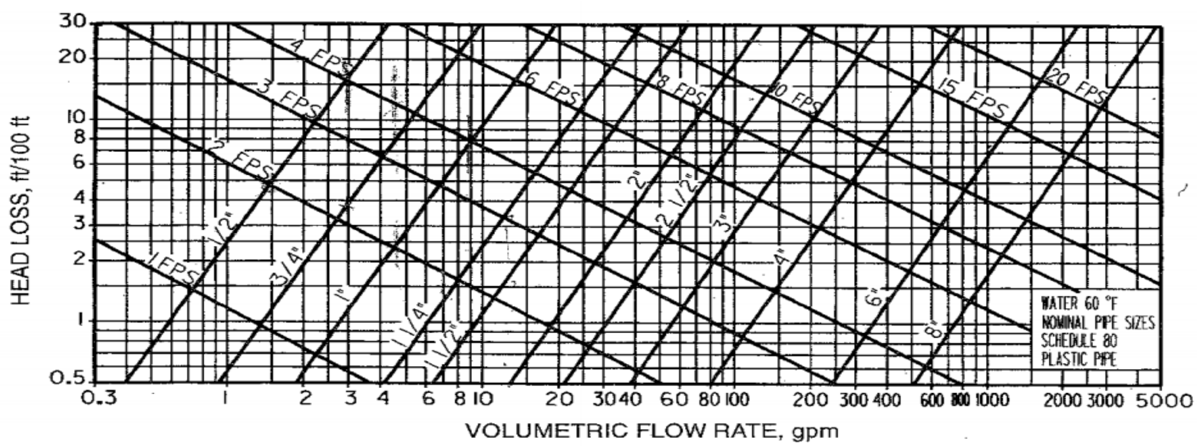


Figure 3-23: Friction Loss for Water in Plastic Pipe (Schedule 80) [67]

The proposed system starts at the outlet of the submersed pump suspended within the buried tank; this design can be seen in Figure 3-24. Upon exiting the tank, a 1½" pipe will direct the water upwards using a 90-degree elbow. The water is then pumped upwards a distance of 33.5 feet up to the peak of the roof within the interior of the warehouse. An exit point, where an open fan currently exists, will allow for the water to be directed outside to the roof peak through a combination of 90-degree elbows and a single tee connection that will create the two horizontal spray lines along either side of the peak of the roof pitch, the equivalent length and head losses were calculated for these connections using Table 3-5 and Figure 3-26. This design is outlined in Figure 3-24 and a close up of the rooftop connection design is demonstrated in figures 3-25.

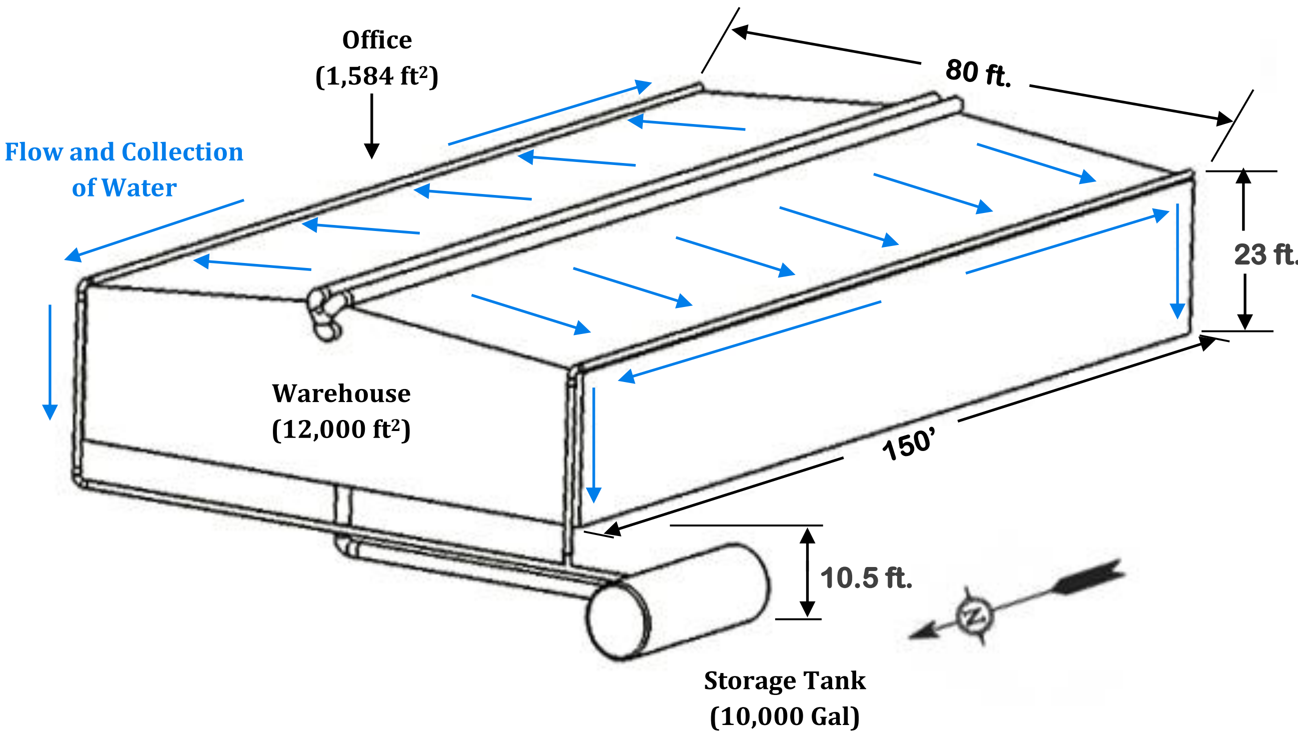


Figure 3-24: Isometric View of Building and Piping Design

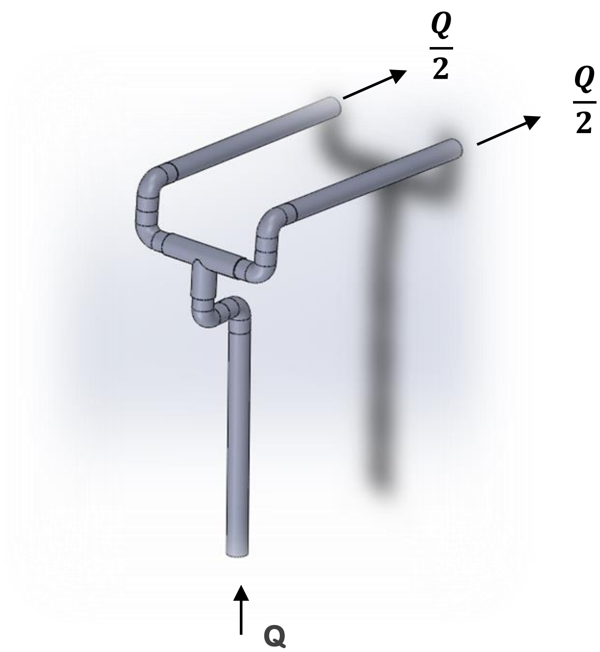


Figure 3-25: Diagram of 90 deg Elbow and Tee Rooftop Connection

Each of these pipe outlets will run along the roof on each side of the peak, with each of these pipes downsizing in three sections. The first section will be 1¼" pipe, the next will be 1" pipe and the last 50 ft section will be sized at ¾" pipe. This will allow for the velocity to stay above the required 2 ft/sec, while maintaining pressure within the system to produce the appropriate "spraying" effect out of the holes. Each section will be 50' long and consist of 75 holes drilled along the outside at the width of the corrugated metal roof to allow for optimal water spray and coverage. The diameter of the holes was calculated through equations 13 and 14, below.

$$\boldsymbol{Q = AV \rightarrow A = \frac{Q}{V}} \qquad \textbf{(14)}$$

$$\boldsymbol{A = \frac{\pi d^2}{4} \rightarrow d = \sqrt{\frac{4A}{\pi}}} \qquad \textbf{(15)}$$

Where, Q is the flowrate in ft^3/sec, A is the area in ft^2, and V is the design velocity in ft/sec, and d is the diameter of the holes to be drilled in the pipe.

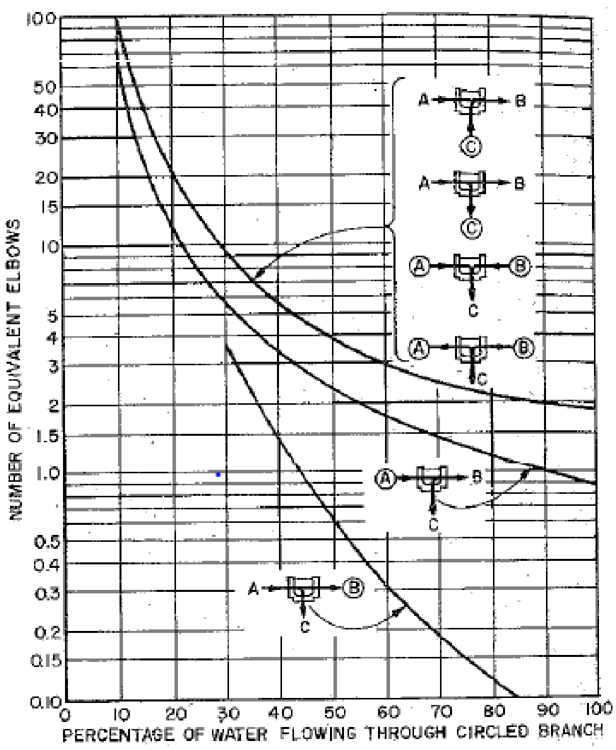
Therefore, in the first two sections, the holes will have a diameter of 0.08" and, in order to account for any pressure losses, the last section will have holes 0.06" in diameter. In addition, a total head loss of 0.25 ft of H_2O was assumed to account for any head loss from the holes along the horizontal spraying pipes. Though it is understood that implementing "spray-nozzles" would allow for optimal evaporation on the roof surface, due to the fact that grey water is being utilized, it is understood that such installments would be prone to clogging and thus were deemed unfit for this design. Furthermore, the slight spraying-effect through the small-diameter holes and pressurized pipes was assumed to allow for sufficient coverage and optimal evaporation rates and cooling effects.

Adding all of the acquired head losses together, along with the head losses from each of the 90-degree pipe elbows and the pipe splitter tee, a pipe-system head loss was calculated to be roughly 22 feet. Accounting for the elevation head of 36.8 ft then resulted in a final total head loss of 57 ft required for the pump to overcome. Table D-1 is a compilation of the pipe analysis and respective head loss and other calculated values and can be found in Appendix D. A layout of this design can be seen in Figure 3-24. It should also be noted that the calculated pressure at the pump discharge was found to be 24.63 psi.

In order to keep the system cycling, the pipe system is to be integrated into the existing gutter and water collection systems on the existing building structure. As demonstrated in Figure 3-24 any excess water that is not evaporated off the roof is simply collected by the gutters and rerouted back through the collection, filtration, main tank, and pump system.

Table 3-5: Equivalent Length in Feet of Pipe for 90° Elbows

Velocity, fps	Pipe Size: 1/2	3/4	1	1-1/4	1-1/2	2	2-1/2	3	3-1/2	4	5	6	8	10	12
1	1.2	1.7	2.2	3.0	3.5	4.5	5.4	6.7	7.7	8.6	10.5	12.2	15.4	18.7	22.2
2	1.4	1.9	2.5	3.3	3.9	5.1	6.0	7.5	8.6	9.5	11.7	13.7	17.3	20.8	24.8
3	1.5	2.0	2.7	3.6	4.2	5.4	6.4	8.0	9.2	10.2	12.5	14.6	18.4	22.3	26.5
4	1.5	2.1	2.8	3.7	4.4	5.6	6.7	8.3	9.6	10.6	13.1	15.2	19.2	23.2	27.6
5	1.6	2.2	2.9	3.9	4.5	5.9	7.0	8.7	10.0	11.1	13.6	15.8	19.8	24.2	28.8
6	1.7	2.3	3.0	4.0	4.7	6.0	7.2	8.9	10.3	11.4	14.0	16.3	20.5	24.9	29.6
7	1.7	2.3	3.0	4.1	4.8	6.2	7.4	9.1	10.5	11.7	14.3	16.7	21.0	25.5	30.3
8	1.7	2.4	3.1	4.2	4.9	6.3	7.5	9.3	10.8	11.9	14.6	17.1	21.5	26.1	31.0
9	1.8	2.4	3.2	4.3	5.0	6.4	7.7	9.5	11.0	12.2	14.9	17.4	21.9	26.6	31.6
10	1.8	2.5	3.2	4.3	5.1	6.5	7.8	9.7	11.2	12.4	15.2	17.7	22.2	27.0	32.0



Notes: 1. Chart is based on straight tees (i.e., branches A, B, and C are the same size).
2. Pressure loss in desired circuit is obtained by selecting the proper curve according to illustrations, determining the flow at the circled branch, and multiplying the pressure loss for the same size elbow at the flow rate in the circled branch by the equivalent elbows indicated.
3. When the size of an outlet is reduced, the equivalent elbows shown in the chart do not apply. Therefore, the maximum loss for any circuit for any flow will not exceed 2 elbow equivalents at the maximum flow occurring in any branch of the tee.
4. Top curve is average of 4 curves, one for each circuit shown.

Figure 3-26: Equivalent Length for Tees (In Terms of Equivalent 90° Elbows)

3.6.5. PUMP

A submersed water pump was selected to be utilized for the roof-spray technology and evaporative system due to the advantages associated within the properties of head loss. Because a smaller pump was required for this system, with the added benefit of being more economical, the submersing of the pump allowed a smaller sized pump to overcome the significant head losses gathered throughout the roughly 362 ft long piping system and 36.8 ft of elevation head. The pump is to be mounted within the buried tank and suspended roughly 6.5 ft above the bottom of the tank so as to reduce the collection of sediments that could harm the pump. A pipe with a mesh filter capping the end will make sure that all water can be reached from the base of the tank.

To size the pump the max flow rate and total head loss calculated from the pipe design were utilized for the proposed system. Table C-2, in Appendix C, features a recommended model of the $389.00 Franklin J-Class Electric Series V Submersible Well Pump (25 GPM - 1 HP - 230 Volts - 2 Wire), and is suitable to handle the expected peak evaporation flow rate of 23 gpm. This pump is rated at 25 GPM with a Total Dynamic Head of 150 ft, 6 Stage Wet End, 1 HP Franklin Electric 4" Single-Phase/60 Hz Motor, and 230 Volt/2-Wire (2 wires + ground) [68]. The specifications for the selected Franklin J-Class Pump can also be found tabulated in Table C-1 and Figure C-4 in Appendix C.

Using the product pump charts from the manufacturer shows that this pump will adequately meet the requirements of providing a flow rate of 23 GPM and a total dynamic head of 57 feet. It should also be noted that, the Franklin 25JV15P4-2W230 pump also meets the requirements for our system and, should that pump prove to be a more economical option, would also be a viable selection for this design.

Another factor involved in pump selection is the efficiency of the pump and the pump shaft power. Based on the pump curve and product specifications, the efficiency of the pump was assumed to have the lowest efficiency of 51%. This pump was also assumed to be a 2-wire, single phase system. Then, using these values and the ratings of the proposed pump, a pump shaft power in wattage was determined using Equation 16:

$$\boldsymbol{W_s = \frac{p*Q*HP}{\zeta_p * g}} \qquad \textbf{(16)}$$

Where p is the pressure in lb/ft^3, Q is the Max flowrate in ft^3/s, HP is the horsepower, ζ_p is the efficiency in feet of H_2O, and g is gravity in 32.2 ft/s^2.

From this, a resulting pump shaft power of 107.09 watts was found for the selected pump that met our system design requirements. Balance and Gate valves will also be implemented into the design at the pump within tank and along the pipe located within the structure so as to allow regulation of the pressures the pump is experiencing and so as to allow for more direct control options.

4. ANALYSIS AND RESULTS

The purpose of this project has been to determine whether Evaporative Roof-spray Technology has potential benefit to the consumer, environment, and society's wastewater treatment systems. It is understood that this is only one of many methods that may work in collaboration to solve the growing issue of stormwater runoff and natural water pollution. This chapter covers the following aspects of this study; amount of runoff generated on test site, stormwater harvesting potential, filtration and pump design parameters, storage tank capacity, evaporation potential, and feasibility analysis.

4.1 AMOUNT OF RUNOFF FOR TEST SITES & STORMWATER HARVESTING POTENTIAL

Precipitation variations for the Monroeville summer season, May 1st through October 31st, were analyzed and verified through supporting calculations. It was found that this region experiences, on average, roughly 239 rainfall occurrences. Of these instances, the average magnitude of these storms equated to roughly 0.326 in/day translating into a total summer rainfall of 59.7 in, based on the McKeesport 2014 meteorological and rainfall data. A compilation of the runoff calculations for the average precipitation experienced by Monroeville can be seen compiled in Table A-5 in Appendix A. These calculations feature the McKeesport 2014 precipitation data, which can be found tabulated in Table A-6 in Appendix A. Furthermore, the Pittsburgh International Airport (PIA) data trends, Table A-7 in Appendix A, were also generated to provide a comparable average rainfall rate of 0.207 in/day with a total precipitation value of 37.9 in. Recall that this PIA data reflects the rainfall average trends recorded for the region from 1981 to 2010, making its resulting average rainfall a more conservative evaluation of the region's expected runoff.

When applying the selected McKeesport data to the 2-acre test lot, the total runoff generated for the site is 8,654 gallons per day, resulting from a runoff rate of 6 gpm. When evaluating the assumed collection surfaces (the test site parking lot and structure) the resulting runoff rate is 3.8 gpm, with a total volume runoff of 5,443 gallons per day on average. When applying the collection coefficient of 0.825 the resulting collectible runoff from the parking lot and structure amounts to 3 gpm or 4,491 gallons per day.

A comparison of these precipitation trends can be seen in Figure 4-1, where the days of the summer, ranging from 121 to 304, correlate to the May 1st-October 31st days of the season. Note that the peak rainfall episodes outlined on the plot ranging from 0 in. rainfall up to approximately 3 in. for the McKeesport data, and roughly 4.6 in for the PIA trend. Furthermore, the peak rainfall month is generally June (day 153-181), whereas the minimum rainfall month is August (day 213-243). A MATLAB code was produced to evaluate the large collections of hourly rainfall data obtained from the PIA and McKeesport databases. The MATLAB code can be found in Appendix F.

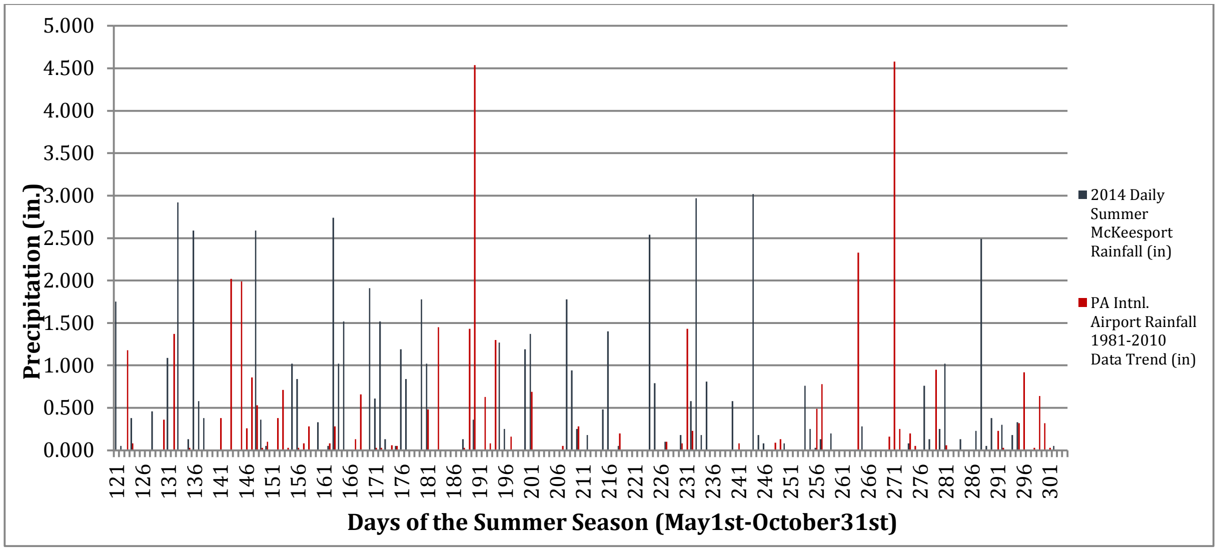


Figure 4-1: Comparison of Normal Average Weekly Precipitation, McKeesport and Pittsburgh International Airport Stations, 1981-2010 [36]

Figure 4-2, below, shows the precipitation amounts based on Allegheny regional rainfall trends [45]. This chart is useful for understanding the amount of rainfall experienced, in inches, with respect to the frequency of occurrence throughout a single month timeframe.

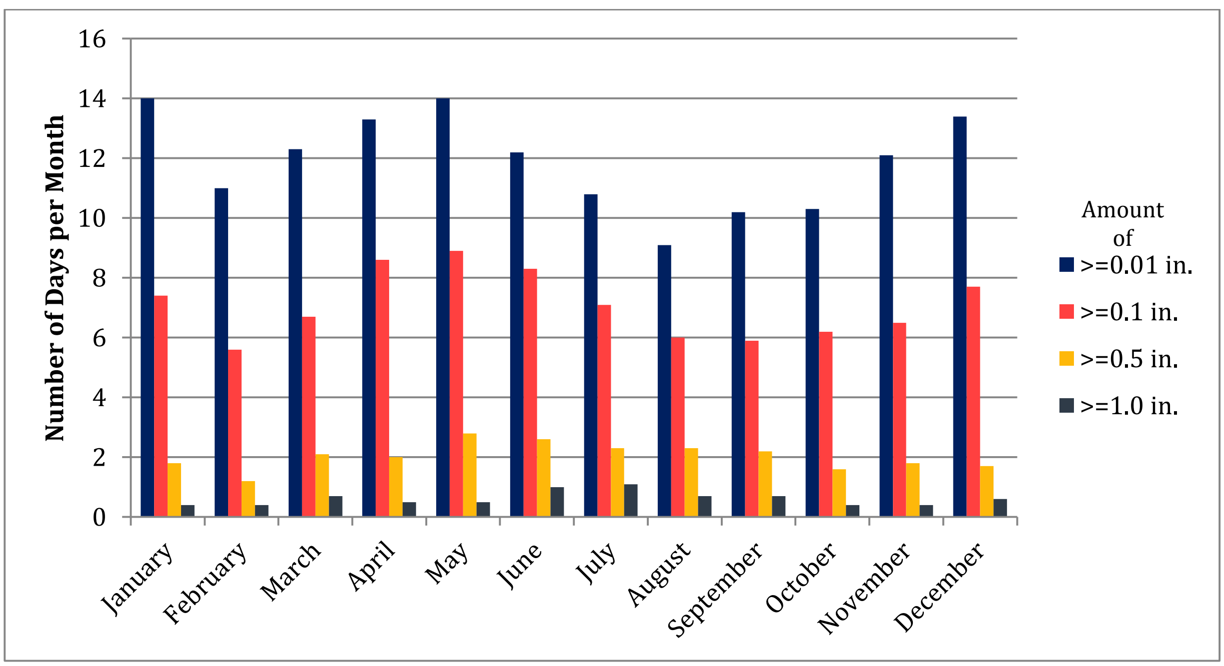


Figure 4-2: Precipitation Amounts Based on Allegheny Regional Rainfall Trends [36]

HDSC and McKeesport collected data estimates the average precipitation event for Monroeville is roughly 0.326 in. of precipitation in 24-hour period. For a 12,000 square foot roof, this type of precipitation event translates to the need to divert and contain 1,811 gallons of rainwater for that 24 hour day.

For this research project, a range of runoff factors and flow rates were analyzed for their assumed significant impact on the Monroeville area. In addition to the average runoff rate determined, the 1-Year and 25-Year recurrence interval storms were also evaluated for the region from the McKeesport metrological data. During the 1 year storm the test site experiences an assumed 2 inches of rainfall over 24 hours, or 0.083 in/hr; and during the 25 year storm this jumps to a rate of 4 in over 24 hours, or 0.167in/hr.

When accounting for the approximately 2.1 acre site surface area, with only 40% of the property urbanized, the 1 year storm would result in 53,093 gallons of stormwater runoff potentially conveyed to the Wastewater Treatment Plant for a single 24 hour period (from all surfaces). From just the building and parking lot alone, this is slightly reduced to roughly 33,394 gallons over the same 24 hours with a runoff rate of 23 gpm. Applying the collection coefficient of 0.825 results in a total of a rate of 19 gpm giving 27,550 gallons over 24 hours collectible from the roof and paved surfaces. Doing the same calculation for the 25 year storm yields a possible collection from the roof and pavement of nearly 55,099 gallons for the 24 hour period. Table 4-1, below, shows a compilation of the calculated runoff for the 1-Year and 25-Year Storms. In addition, the 1-Year and 25-Year storms evaluations can be found compiled in Tables A-3 and A-4, of Appendix A.

Table 4-1: Collection Amounts by Area

CALCULATED RUNOFF	1 Year Storm		25 Year Storm	
	Rate (gpm)	Amount (Gallons)	Rate (gpm)	Amount (Gallons)
Warehouse Roof (Steel)	7.7	11,109	18.1	26,068
Office Roof (Steel)	1.0	1,468	2.4	3,447
Paved Ground Surface (Asphalt)	14.5	20,816	34.1	49,046
Unaltered/Natural Ground Cover	13.7	19,699	36.8	52,984
Total Runoff Potential	36.9	53,093	91.4	131,545

Analysis of the the Sewer Overflow Advisory Key for overflow alerts showed that the peak episodes of rainfall during this window occur during the months of June and October and can be seen verified by Table 4-1. Table 4-2 outlines the approximate hours during the summer that the Allegheny Sanitary Authority experiences overflow and must dump excess sewage into the nearby rivers. It was assumed that the analysis of the 2015 Overflow alert showed a unique instance where excess rainfall fell for the month of October, whereas the PIA 1981-2010 climate trends for the region support that June is the primary rainfall month for this region. Episodes of least rainfall occurred during the month of August, with July also fairly dry.

Table 4-2: Estimation and Evaluation of SOAK Overflow Advisory Alerts

Month	Approx. # Hours CSO Advisory Active	Total Hours for Month	% Time Overflow Advisory in Effect
May	34.75	744	5%
June	63.1	720	9%
July	44.2	744	6%
August	9	744	1%
September	39.6	720	6%
October	81.6	744	11%

* The "Sewer Overflow Advisory Key (SOAK) alerts the public when overflows in the ALCOSAN collection system are impacting area waterways during ALCOSAN's NPDES permit summer reporting period, May 1 to October 31" [18].

4.2 FILTRATION & PUMP RATE

Based on the selected filter for the design elements of this project analysis, it is possible to filter at a maximum rate of 10.7 gal/sec, or 642gpm, easily allowing for the peak 1-year storm runoff collection rates of 23.2 gpm while accommodating the demands of the pump which require a maximum flowrate of 21 to 30 gpm, satisfying the maximum evaporation demand of 23 gpm. Most commercial filtration systems are sized for larger flowrate capabilities than the test site will experience, therefore it was assumed to be more economical to pick an oversized filter already on the market. It should also be noted that, for this design the pump rate could not exceed that of the filtration rate or else the system would be unable to maximize its potential evaporation time and resulting cooling impact. The required pump shaft power to accommodate the maximum evaporation rate and head losses was found to be 107.09 Watts, for the 1 HP Franklin pump.

4.3 STORAGE

The premise for the sizing of the storage tank began with the understanding and assumption that it would be economically and spatially infeasible to attempt to store all of the collected 27,550 gallons from a one-year storm. Therefore, it was presumed that the consumer for our test site would desire to size the tank based on how much they want to offset with respect to the initial installment costs. Therefore a financial analysis of possible tanks was utilized in determining the appropriate capacity. Therefore the selected tank would provide the most optimal payback return over an assumed (pump) lifespan of 15 years, while minimizing the amount of time that the tank is either empty or beyond max capacity since these allude to timeframes where evaporation and, in turn any air conditioning offset return, is impossible. The resulting Air Conditional value or "cooling potential" of the 10,000 gallon tank is $786.46, whereas a 5,000 gallon tank yields an equivalent cooling value of $649.21. This 10,000 gallon tank was found to be full, and risking overflow, 5% of the time and empty 51% of the time.

4.3.1. ANALYSIS OF SELECTED TANK CAPACITY

The estimated rainfall runoff on the Monroeville site for a 1-year storm is 53,093 gallons (reference Table A-3). Unfortunately, a tank of this magnitude would be impractical to implement due to its large size and expensive cost. Therefore, the relationship between the evaporation potential of the roof-spray technologies, and the pattern of rainfall for the region was evaluated, in combination with the test site owner's requirements. This generated Table B-1, in Appendix B, showing the amount of time a given size tank would be either full or empty. To note it was assumed that, when the tank is full, the system will not be able to collect additional water, whereas, if the tank is empty, the system will not be able to evaporate any water back into the atmosphere, making these two extremes the weak points in the evaporative technologies application. Figures 4-3 and 4-4 evaluate the volume withheld with respect to the amount of rainfall collected for the expected maximum (June) and minimum (August) rainfall months. In these plots, the horizontal lines denote the set capactiy for three size tanks of interest. Each trendline, denoted with a tank's corresponding color, shows the change in volume of water within the tank. These values will increase and decrease at the same rate, because the evaporatin and collection rates are not dependent on the tank size. The notable differences come in the amount of time each tank contains water where the larger tanks will, correspondingly, have more time before draining to empy. The plots were restricted at the 15,000 gallon mark because any tank sized above this capacity proved too costly financially and spatially for the test site property owner. Furthermore, after completing financial analysis of the tank's depreciative values, it was found that this would not afford enough of a return on investment for the client. Figure B-1 in Appendix B shows data trends surrounding the amount of overflow experienced by these 5,000, 10,000, and 15,000 gallon tanks.

Volume Withheld and Corresponding Tank Capacities for June

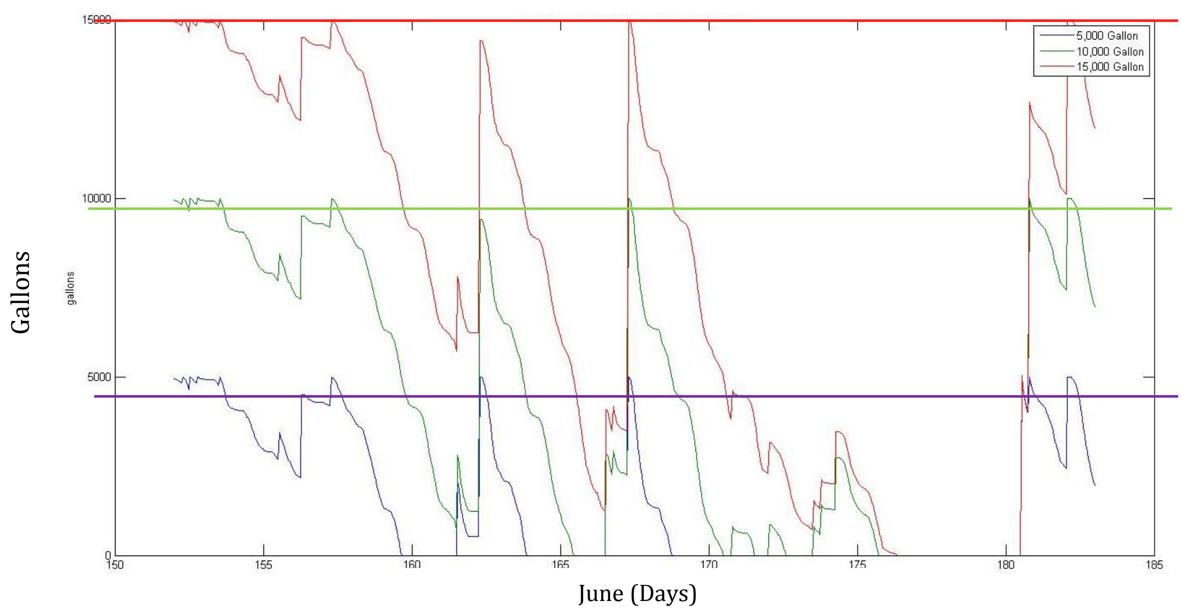


Figure 4-3: June Evaluation of Tank Volume Withheld Over Time (Based on the PIA Data Trends)

Volume Withheld and Corresponding Tank Capacities for August

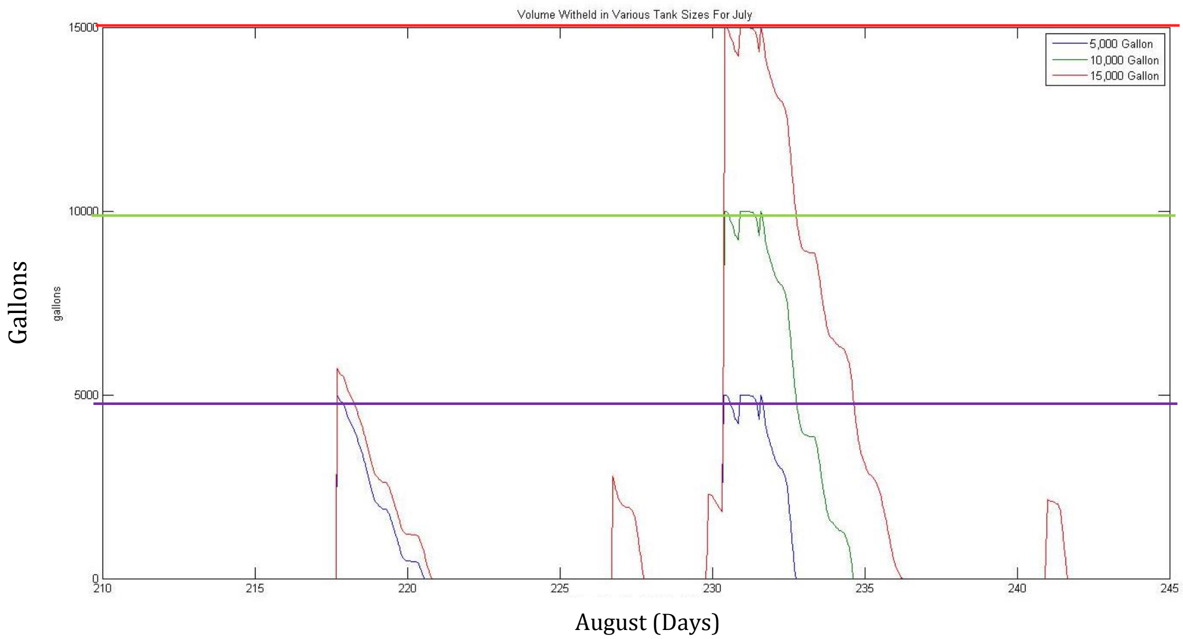


Figure 4-4: August Evaluation of Tank Volume Withheld Over Time (Based on the PIA Data Trends)

Based on the trends of Figure 4-3 and Figure 4-4, and Table B-1 in Appendix B, it can be seen that increasing the tank capacity initially results in a significant reduction in the hours the tank is either full or empty. Understandably, increasing the tank's capacity results in a reduction in the time that the tank would be either full or empty.

It is assumed that it is impossible to store all of the water harvested, both economically and/or spatially, and therefore the design requires the installment of an overflow outlet and valve system to account for peak and sudden rainfall episodes. This discharge will offset the grey water, now treated, into the nearby collection pond on site of the test location. Future developments of this system and its integrated technologies would also allow for the future attachment of other evaporative technologies to offset these overflows. Table B-1 in Appendix B shows data calculations regarding the expected overflow volumes with their respective tank capacities.

For the tank capacity selection, it was found that there was no clear support of one tank size over another with respect to economics or rainfall. This system will provide the most return through its ability to allow for further site development and its ability to offset runoff from the main sewage collection system. Therefore, the sizing of the tank needs to be based on the amount of gallons needed to be offset by the selected property to meet EPA stormwater runoff regulations. Therefore, the selection of a tank size becomes the decision of the property owner based on (1) the type of financial investment they are willing to make, and (2) how much runoff they desire or need to offset from the main sewage collection system.

4.3.2. FINANCIAL ANALYSIS OF SELECTED 10,000 GALLON TANK

By considering the upfront investment of the different capacity tanks and the potential for savings in the form of air conditioning energy, a financial investment analysis can be performed to see which tank size provides the business owner with the greatest investment. Referencing Table B-1 in Appendix B, the equivalent electrical value of cooling potential was applied for the various tank sizes considered. The found value of cooling potential for these tanks was, not only based on the assumed EER of 7, but also the amount of time that the tank is being utilized in the form of effective percentage times that the tank is either at full or empty capacity.

Two tank sizes, in particular, were noted to give the test site client a wide range of options. The first and the most economical option is the 5,000 gallon tank. When only accounting for electrical savings in the form of cooling effect, this tank will achieve a breakeven in its 27th year of usage. The second tank evaluated was the client's selected 10,000 gallon capacity storage unit. This tank will receive its breakeven point 33 years into its life. Unfortunately, in both these scenarios, it is clear that this equipment will not pay for itself within its own lifetime if you only account for electrical savings. Therefore, one must also consider other potential sources of return in order to offset the initial unit costs of this technology. Other sources that provide a prospective return on investment include; the monetary equivalent for productivity versus temperature savings, tax credits, elimination of fines, etc., all of which could allow for significant return to potentially offset the depreciative costs of the tank.

Table B-2 and B-3 in Appendix B shows the cost analysis, accounting for taxes and depreciation for both the 5,000 and 10,000 gallon tanks. This system was assumed to be classified as a "land improvement" type investment, with a 20 year recovery period. For both tanks a business effective tax rate of 34% as assumed, and the depreciation was inferred from Internal Revenue Service (IRS) depreciation tables [69] [70][83] [71].

Assuming a life-span of twenty years, based on the life-expectancy of a typical water pump, and a minimum acceptable rate of return (MARR) of 2.5%, the Annual Worth Method was used to calculate the optimal investment option for prospective consumers. The results of this analysis are illustrated in Table 4-3 and Figure 4-5. This further confirms that there is no economic benefit to increasing the size of the tank. Therefore, when comparing this information with Table B-1 in Appendix B that illustrate the projected amount of time a given capacity tank would be either full or empty, it is possible to justify the 10,000-gallon tank investment as it would be needed when attempting to reduce the 1-Year and 25-Year storm episodes, further supporting the clients decision.

Table 4-3: Tank Investment Annual Worth Evaluation

Tank Size (gallons)	Investment (Cost of Tank Equipment)		Value of Cooling Potential * Assumed: EER = 7	Annual Worth (20 year recovery)	
1000	$	(10,967.80)	$404.48	$	(143.91)
2000	$	(12,418.90)	$499.58	$	(121.37)
3000	$	(13,870.00)	$559.59	$	(133.91)
4000	$	(15,321.10)	$611.43	$	(154.63)
5000	$	(16,772.20)	$649.21	$	(189.40)
6000	$	(18,223.30)	$678.28	$	(232.89)
7000	$	(19,674.40)	$710.13	$	(273.59)
8000	$	(21,125.50)	$738.32	$	(317.96)
9000	$	(22,576.60)	$763.97	$	(364.86)
10000	$	(24,027.70)	$786.46	$	(414.93)
11000	$	(25,478.80)	$803.90	$	(470.04)
12000	$	(26,929.90)	$821.26	$	(525.24)
13000	$	(28,381.00)	$839.34	$	(579.71)
14000	$	(29,832.10)	$859.60	$	(632.01)
15000	$	(31,283.20)	$873.42	$	(690.74)

* "( )" denotes negative value

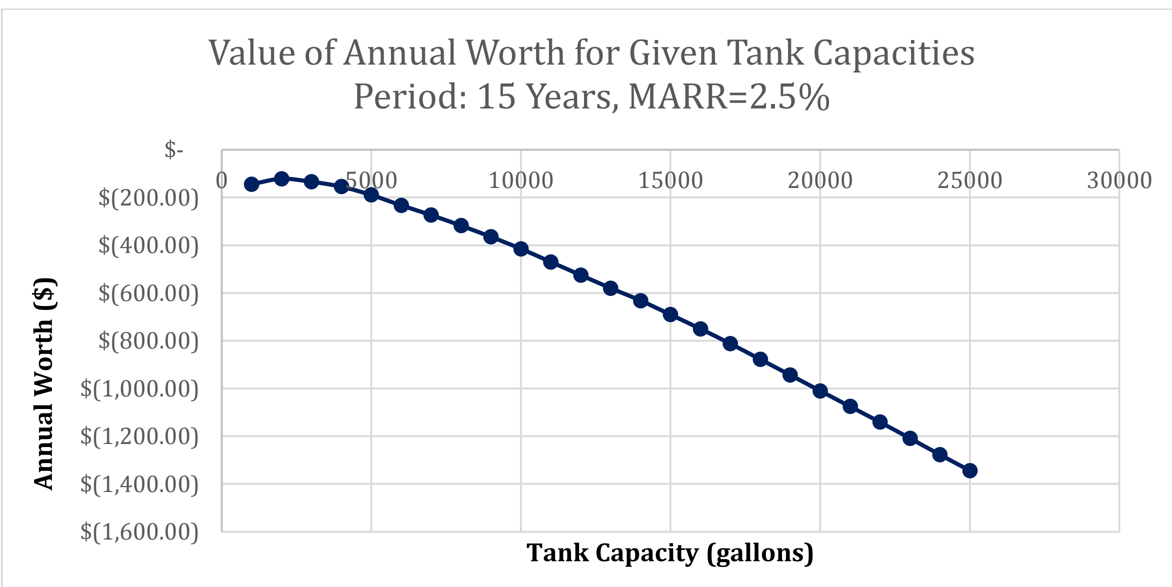


Figure 4-5: Annual Worth Trend for Various Tank Capacities

4.4 EVAPORATION

Due to the cooling effects of evaporation, the average and maximum roof temperatures were reduced within the system calculations. Therefore, with the Evaporative Roof-spray Technology installed on the test roof, the rooftop temperatures varied from a maximum of 30.5°C (86.9°F) to a minimum of -4.40°C (24.08°F), with an average temperature of 17.4°C (63.32°F). Comparing this to the average summer rooftop temperatures for that region further supports the concept that the designed system will reduce summer solar heating effects through a structure's roof. Using the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) assumed 2% design for rooftop temperature analysis in June through August, rooftop conduit temperatures in the Pittsburgh, PA region can experience temperatures as high as 150°F [72].

A maximum evaporation rate of 23 gpm was also verified. When calculating, designing and sizing the piping and pump components of the system, this maximum value was accounted for, even though the expected average evaporation rate is 2.84 gpm. The average evaporation rate of 2.84 gpm was used in the evaluation of daily tank capacities and evaporative trends. Assuming a daily evaporation time of 12 hours, the amount of time required to evaporate a full 10,000 gallon tank was found to be 5 days. Rainfall episodes occur approximately74 days out of the 183 day season, translating into a rainfall occurrence frequency of 40.4%.

The potential for the evaporative cooling spray roof technology can be calculated for one summer month assuming the maximum evaporation rate of 23 gpm is effective for 12 hours of evaporation time, every day. At the maximum evaporation rate, the spray roof technology has the potential to offset 16,560 gallons daily, and 531,360 gallons for a 31-day month. The average 2.84 gpm will applicable more commonly throughout the summer, the resulting evaporation over the daily evaporation time of 12 hours is 2,045 gallons, translating into 63,389 gallons for a 31-day month.

4.5 PRODUCTIVITY VS. TEMPERATURE

Using Figure 3-15 in section 3.4, the average interior summer temperature of 26.67°C (80°F), and the assumed 25°C (77°F) desired working temperature, a percentage increase of productivity due to more comfortable working conditions was interpreted. Aligning the corresponding temperatures with where they intersect with the productivity curve a relative performance range was determined from 97.5-98.5%, equating to a (minimum) 1% increase in productivity when interior building temperatures are reduced. Then, applying this percentage increase to the test site company's annual revenue of $1,000,000.00, translates into a potential $10,000 annual productivity monetary savings. This value was then considered in the final feasibility analysis of the system.

4.6 FEASIBILITY ANALYSIS

A feasibility analysis was conducted evaluating the materials cost of the system defined in this study. Accounting for the cost of the filter, storage tank, pump, and the piping required to harvest and create the spray roof system, and was compiled in Table 4-4. It was found that installment costs range from approximately $17,600 to $26,700. It should be noted that this analysis excludes any installation and excavation costs due to the notion that this is site dependent. Although the lifespan of the components vary, it is assumed that the only necessary replacement and maintenance costs will come after 15 years of service, at which point the pump may need replacing, depending on the activity of the system will be to "return urban environments back to Mother Nature."

Table 4-4: Materials List and Associated Equipment Costs

Item	Number of Units	Total Cost
Filter	1	$1,579.95
Storage Tank	1	$24,027.70
Pump	1	$389.00
Schedule 80 PVC Pipe	363 Ft.	$703.35
Total	1	$26,700.00

Though there exists minimal potential for noticeable energy savings and return on investment solely in the form of offsetting AC and cooling energy costs, the primary driving force that will encourage the proliferation of this technology is its ability to reduce stormwater runoff from localized sites. Because of the perpetually increasing implementation of more stringent environmental regulations within communities all over the United States, independent landowners now face heightened legislative restrictions regarding the amount of stormwater runoff leaving their property and entering the primary sewage collection systems. With the water-focused regulations already becoming more and more ambitious in their efforts to reduce harmful stormwater runoff and wastewater treatment plant overflows, private landowners will be surely forced into adopting water conserving technologies. Because of this, private landholders will begin to seek out more cost-effective environmental water-conserving technologies, especially those that offer some form of return on investment, whether that be in the form of cooling, tax reprieves, or reductions in fines and pass-through costs from the regional wastewater treatment plant. Spray roof cooling technology is a solution, with the potential to offset as much as current green-technologies currently on the market. Therefore, it is understood that the evaporative roof-spray technology, though does not show substantial returns in cooling energy cost offsets, does show the potential to offset considerable amounts of runoff and, therefore, becomes a suitable alternative solution for landowners to appease the legislature and avoid fines resulting from not adhering to more stringent runoff regulations. Furthermore, when applied to working environments, this technology offers further potential for returns regarding the concepts of temperature versus productivity and an employee's ability to be more comfortable and work harder with more moderate workroom temperatures.

The final evaluation of the potential return on investment for this system takes into account depreciation, taxable savings, annual operating costs, annual electrical savings, and annual productivity savings based on company revenues (see Table 4-5). A depreciation factor of 0.0375, derived from IRS depreciation tables was used to find the total depreciation experienced by the equipment. Taxable savings were based on this system being classified as a "land improvement" type investment, with a 20-year recovery period. Annual system operating costs accounted for the electrical costs needed to run the system, primarily from the usage of the pump, and an assumed electrical cost of $0.08. The annual electrical savings were based on the potential cooling electrical offset from the 10,000 gallon tank. Finally, the annual productivity savings were assumed based on the desired building cooling effect and a 1% relative increase in potential productivity revenues gained. Accounting for the potential returns allows for a return on investment in under 3 years.

Table 4-5: Total Value Analysis of System Apparatus

10,000 Gallon Tank Year	Before Tax Cash Flow (BTCF)	Depriciation	Taxable Savings	Tax	After Tax Cash Flow (ATCF)	Annual System Operating Costs	Annual Electric Savings	Annual Productivity Savings	Total Value
0	$ (26,700.00)		$ -	$ -	$ (26,700.00)				$ (26,700.00)
1	$786.46	$ (1,001.25)	$ (214.79)	$ -	$ 786.46	$ (43.98)	$ 786.46	$ 10,000.00	$ (15,215.05)
2	$786.46	$ (1,927.47)	$ (1,141.01)	$ 387.94	$ 1,174.40	$ (43.98)	$ 786.46	$ 10,000.00	$ (3,298.17)
3	$786.46	$ (1,782.76)	$ (996.30)	$ 338.74	$ 1,125.20	$ (43.98)	$ 786.46	$ 10,000.00	$ 8,569.51
4	$786.46	$ (1,649.26)	$ (862.80)	$ 293.35	$ 1,079.81	$ (43.98)	$ 786.46	$ 10,000.00	$ 20,391.80
5	$786.46	$ (1,525.37)	$ (738.91)	$ 251.23	$ 1,037.69	$ (43.98)	$ 786.46	$ 10,000.00	$ 32,171.96
6	$786.46	$ (1,411.10)	$ (624.64)	$ 212.38	$ 998.84	$ (43.98)	$ 786.46	$ 10,000.00	$ 43,913.27
7	$786.46	$ (1,305.10)	$ (518.64)	$ 176.34	$ 962.80	$ (43.98)	$ 786.46	$ 10,000.00	$ 55,618.55
8	$786.46	$ (1,207.37)	$ (420.91)	$ 143.11	$ 929.57	$ (43.98)	$ 786.46	$ 10,000.00	$ 67,290.59
9	$786.46	$ (1,191.35)	$ (404.89)	$ 137.66	$ 924.12	$ (43.98)	$ 786.46	$ 10,000.00	$ 78,957.19
10	$786.46	$ (1,191.09)	$ (404.63)	$ 137.57	$ 924.03	$ (43.98)	$ 786.46	$ 10,000.00	$ 90,623.70
11	$786.46	$ (1,191.35)	$ (404.89)	$ 137.66	$ 924.12	$ (43.98)	$ 786.46	$ 10,000.00	$ 102,290.30
12	$786.46	$ (867.42)	$ (80.96)	$ 27.53	$ 813.99	$ (43.98)	$ 786.46	$ 10,000.00	$ 113,846.76
13	$786.46	$ (867.42)	$ (80.96)	$ 27.53	$ 813.99	$ (43.98)	$ 786.46	$ 10,000.00	$ 125,403.23
14	$786.46	$ (867.42)	$ (80.96)	$ 27.53	$ 813.99	$ (43.98)	$ 786.46	$ 10,000.00	$ 136,959.69
15	$786.46	$ (867.42)	$ (80.96)	$ 27.53	$ 813.99	$ (43.98)	$ 786.46	$ 10,000.00	$ 148,516.15
16	$786.46	$ (867.42)	$ (80.96)	$ 27.53	$ 813.99	$ (43.98)	$ 786.46	$ 10,000.00	$ 160,072.61
17	$786.46	$ (867.42)	$ (80.96)	$ 27.53	$ 813.99	$ (43.98)	$ 786.46	$ 10,000.00	$ 171,629.07
18	$786.46	$ (867.42)	$ (80.96)	$ 27.53	$ 813.99	$ (43.98)	$ 786.46	$ 10,000.00	$ 183,185.54
19	$786.46	$ (867.42)	$ (80.96)	$ 27.53	$ 813.99	$ (43.98)	$ 786.46	$ 10,000.00	$ 194,742.00
20	$786.46	$ (867.42)	$ (80.96)	$ 27.53	$ 813.99	$ (43.98)	$ 786.46	$ 10,000.00	$ 206,298.46

* "( )" denotes negative value

4.7 SUMMARY

It was shown that Evaporative Roof-spray Technology, if implemented on a system-wide basis, has the potential to have a substantial impact on the alleviation of stormwater runoff collected by the main sewage collection system. Furthermore, this is a viable technology, with numbers generated by this study, and it now has the potential to be implemented and tested, and should be.

5. CONCLUSIONS

It was premise of this thesis that the current Allegheny wastewater treatment plant is experiencing a surplus of sewage. This was understood to be mostly due to the increasing amounts of rainfall, as shown in the collected climate data, flooding into the sewage collection system. This has led to consistent discharges into natural waterways, and as much as a potential 53.2% overstress. It was also shown that, while spray roof technology lacks the evaporation strength to overcome a 25-year storm, it is capable of slightly reducing and offsetting peak discharge hours resulting from 1-year storms and making these extreme-scenarios more manageable for the treatment facility. Therefore, based on this study, it was proven that evaporative roof-spray technology has the potential to offset stormwater runoff into the main sewer collection system, while having a cooling effect on the building it is applied to with air conditioning offset potential.

This thesis was able to successfully design a sample roof-spray technology that was shown to effectively offset stormwater runoff from entering the main sewage collection system. The various evaporation evaluations showed the ability to effectively eliminate excess runoff from the test site, with the added cooling effect which generated electrical savings in the form of cooling costs averted.

Furthermore, a key concept of the spray-roof technology was its ability to provide a potential return on investment. This return is substantial when one considers its effect on the "green technology" market. Current EPA and environmental regulations as so focused on addressing the issues at hand that they often neglect investigations into potential returns for the consumer. With any energy saving potential, such technologies begin to generate attention towards the opportunity to develop and propagate further return on investment green technologies.

Another beneficial characteristic of the design outlined in this thesis, is that the system was created with the intent and flexibility of being either retrofitted to existing structures, or adapted through the collaboration and integration of various other evaporative green technologies. This was exemplified by the test site in Monroeville, where any overflows experienced by the collection tank at peak rainfall hours is directed to the nearby natural retention pond.

It was discovered, though, that in order to more effectively apply energy saving concepts the roof-spray technology cannot stand alone. Not only must this technology be implemented across various private properties in order to, working together, generate a larger relief impact on the primary collection system, but it also becomes a necessity to integrate other environmental stormwater-managing technologies if rainfall episodes are expected to increase over the next several decades.

6. RECOMMENDATIONS

The next steps to be taken to advance this research project should, firstly, consider the analysis of rainfall collection and evaporation for of the entire calendar year, including winter months by developing a method of calculating sleet and snow runoff. Additionally, actions should be made to implement a prototype of this design for real time testing and data results. When building the test experiment; temperature, rain, wind, and solar sensors, among others, should be utilized to provide measured data for the test site being evaluated for the full year. Furthermore, rain and solar data should be collected in shorter intervals than "hours" so that more precise evaporation and rainfall trends can be developed. Data evaluations should be conducted for at least 1-year in order to properly size all components and determine measured values that will replace many of the assumptions of this thesis. This data will then be evaluated and analyzed in comparison to the predictions of initial evaporative roof-spray studies, such as the one outlined in this thesis. The collected test data can then be used to further refine current calculations and methodologies in order to refine their output. After testing is completed, the scope of the project will be reevaluated, at which time newer technologies and techniques will be evaluated for their potential to be integrated within these evaporative simulations of Mother Nature, and how they will be optimally utilized by urban societies.

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A. APPENDIX A

RUNOFF CALCULATIONS

Table A-1: Runoff Coefficients (C) for the Recurrence Interval <= 10 Years [6]

	Return Period/Recurrence Interval (years)						
Surface Characteristics	2	5	10	25	50	100	500
Developed:							
Asphaltic	0.73	0.77	0.81	0.86	0.9	0.95	1
Conceret/Roof	0.75	0.8	0.83	0.88	0.92	0.97	1
Grass Areas (lawns, parks)							
Poor Condition(grass covering less than 50% of the area)							
Flat, 0-2%	0.32	0.34	0.37	0.4	0.44	0.47	0.58
Average 2-7%	0.37	0.4	0.43	0.46	0.49	0.53	0.61
Steep, Over 7%	0.4	0.43	0.45	0.49	0.52	0.55	0.62
Fair Condition (gras covering 50-75% of the area)							
Flat, 0-2%	0.25	0.28	0.3	0.34	0.37	0.41	0.53
Average 2-7%	0.33	0.36	0.38	0.42	0.45	0.49	0.58
Steep, Over 7%	0.37	0.4	0.42	0.46	0.49	0.53	0.6
Good Condition (gras covering more than 75% of the area)							
Flat, 0-2%	0.21	0.23	0.25	0.29	0.32	0.36	0.49
Average 2-7%	0.29	0.32	0.35	0.39	0.42	0.46	0.56
Steep, Over 7%	0.34	0.37	0.4	0.44	0.47	0.51	0.58
Undeveloped:							
Cultivated land							
Flat, 0-2%	0.31	0.34	0.36	0.4	0.43	0.47	0.57
Average 2-7%	0.35	0.38	0.41	0.44	0.48	0.51	0.6
Steep, Over 7%	0.39	0.42	0.44	0.48	0.51	0.54	0.61
Pasture/Range							
Flat, 0-2%	0.25	0.28	0.3	0.34	0.37	0.41	0.53
Average 2-7%	0.33	0.36	0.38	0.42	0.45	0.49	0.58
Steep, Over 7%	0.37	0.4	0.42	0.46	0.49	0.53	0.6
Forest/Woodlands							
Flat, 0-2%	0.22	0.25	0.28	0.31	0.35	0.39	0.48
Average 2-7%	0.31	0.34	0.36	0.4	0.43	0.47	0.56
Steep, Over 7%	0.35	0.39	0.41	0.45	0.48	0.52	0.58

**Note: The values in this table are the standards used by the City of Austin, Texas. Used with Permission.*

Table A-2: Runoff Coefficients (C) for Use in Rational Method [6]

Description of Area	Runoff Coefficients	Surface Characteristics	Runoff Coefficients
Businesses:		Pavement:	
Downtown	0.70-0.95	Asphalt or Concrete	0.70-0.95
Neighborhood	0.50-0.70	Brick	0.70-0.85
Residential:		Roofs:	
Single Family Property	0.30-0.50	Lawns, Sandy Soil	
Multiunit (detached)	0.40-0.60	Flat 2%	0.05-0.10
Multiunit (attached)	0.60-0.75	Average, 2-7%	0.10-0.15
Residential (suburban)	0.25-0.40	Steep, x > 7%	0.15-0.20
Apartment	0.50-0.70	Lawns, Heavy Soil	
Industrial		Flat, 2%	0.13-0.17
Light	0.50-0.80	Average, 2-7%	0.18-0.22
Heavy	0.60-0.90	Steep, x > 7%	0.25-0.35
Parks or Cemeteries	0.10-0.25		
Railroad Yard	0.20-0.35		
Unimproved	0.10-0.30		

Source: "Design and Construction of Sanitary and Storm Sewers" ASCE Manual of Practice No. 37, revised by Earl Jones Jr., 1970.

***For 25- to 100- year recurrence intervals, multiply coefficient by 1.1 and 1.25 respectively, and the product cannot exceed 1.0**

Table A-3: 1-Year Peak Discharge Runoff Calculations

Land Development Handbook Formula for Peak Discharge					Lot Size:	2.102	Acres	91563.12	ft^2			
1 YEAR Storm -- Assume: 2" over 24 hours												
	Surface Area (drainage area) (A)	Surface Area (drainage area) (A)	Inches Rainfall	Rainfall Rate/intensity (i)	Surface Runoff Coefficient (C)	Correction Factor for PA (C_f)	Duration of Storm	Peak Discharge Rate (Qp)	Peak Discharge Rate (Qp)	Peak Discharge Rate (Qp)	Peak Discharge Rate (Qp)	Total Collectable Runoff Volume for 24 hr Period
	ft^2	acres	in	in/hr	-	-	hours	cfm	gal/s	gal/hr	gpm	gallons
Warehouse (steel roof)	12000	0.275	2	0.083	0.75	N/A	24	0.017	0.129	463	7.7	11109
Office (steel roof)	1584	0.036	2	0.083	0.75		24	0.002	0.017	61	1.0	1469
Parking Lot (Asphalt)	23041	0.529	2	0.083	0.73		24	0.032	0.241	867	14.5	20816
Ground/Grass (good condition, 2-7% slope	54938	1.2612	2	0.083	0.29		24	0.030	0.228	821	13.7	19699
*Ref Tables 21.10 and 21.10a from Handbook for "C"							TOTAL RUNOFF:	0.082	0.614	2212	36.9	53093
			TOTAL RUNOFF (excluding ground runoff):					0.052	0.386	1391	23.2	33394
			Collection Coefficient:		0.825		Collectible:	0.042626	0.319	1148	19.1	27550

Table A-4: 25-Year Peak Discharge Runoff Calculations

Land Development Handbook Formula for Peak Discharge					Lot Size:	2.102	Acres	91563.12	ft^2			
25 YEAR Storm -- Assume: 4" over 24 hours												
	Surface Area (drainage area) (A)	Surface Area (drainage area) (A)	Inches Rainfall	Rainfall Rate/intensity (i)	Surface Runoff Coefficient (C)	Correction Factor for PA (C_f)	Duration of Storm	Peak Discharge Rate (Qp)	Peak Discharge Rate (Qp)	Peak Discharge Rate (Qp)	Peak Discharge Rate (Qp)	Total Collectable Runoff Volume for 24 hr Period
	ft^2	acres	in	in/hr	-	-	hours	cfm	gal/s	gal/hr	gpm	gallons
Warehouse (steel roof)	12000	0.275	4	0.167	0.88	N/A	24	0.040	0.302	1086	18.1	26068
Office (steel roof)	1584	0.036	4	0.167	0.88		24	0.005	0.040	144	2.4	3447
Parking Lot (Asphalt)	23041	0.529	4	0.167	0.86		24	0.076	0.568	2044	34.1	49046
Ground/Grass (good condition, 2-7% slope	54938	1.2612	4	0.167	0.39		24	0.082	0.613	2208	36.8	52984
*Ref Tables 21.10 and 21.10a from Handbook for "C"							TOTAL RUNOFF:	0.204	1.523	5481	91.4	131545
			TOTAL RUNOFF (excluding ground runoff):					0.122	0.909	3273	54.6	78561
			Collection Coefficient:		0.825		Collectible:	0.100281	0.750	2701	45.0	64813

Table A-5: Monroeville Average Rainfall Peak Discharge Runoff Calculations

`					Lot Size:	2.102	Acres	91563.12	ft^2			
AVERAGE PA Storm -- Assume: 0.215" over 24 hours												
	Surface Area (drainage area) (A)	Surface Area (drainage area) (A)	Inches Rainfall	Rainfall Rate/intensity (i)	Surface Runoff Coefficient (C)	Correction Factor for PA (C_f)	Duration of Storm	Peak Discharge Rate (Qp)	Peak Discharge Rate (Qp)	Peak Discharge Rate (Qp)	Peak Discharge Rate (Qp)	Total Collectable Runoff Volume for 24 hr Period
	ft^2	acres	in	in/hr	-	-	hours	cfm	gal/s	gal/hr	gpm	gallons
Warehouse (steel roof)	12000	0.275	0.215	0.009	0.75	N/A	24	0.002	0.014	50	0.8	1194
Office (steel roof)	1584	0.036	0.215	0.009	0.75		24	0.000	0.002	7	0.1	158
Parking Lot (Asphalt)	23041	0.529	0.215	0.009	0.73		24	0.003	0.026	93	1.6	2238
Ground/Grass (good condition, 2-7% slope	54938	1.2612	0.215	0.009	0.29		24	0.003	0.025	88	1.5	2118
*Ref Tables 21.10 and 21.10a from Handbook for "C"							TOTAL:	0.009	0.066	238	4.0	5707
							TOTAL (excluding ground runoff):	0.006	0.042	150	2.5	3590
					Collection Coefficient:	0.825		Collectible:	0.034278	123	2	2962

Table A-6: CN Method
1-Year Peak Discharge Runoff Calculations

1 YEAR Storm -- Assume: 2 in over 24 hrs		*CN Method								
	Surface Area	Rate of Rainfall	Infiltration Rate	Runoff	Storm Duration	Runoff	Volume of Runoff	Rate Volume of Runoff	Runoff Rate	Total Runoff
	ft^2	in/hour	in/hour	in/hour	hours	in	ft^3	ft^3/hr	gpm	gal
Wearhouse	12000	0.083	0	0.083	24	2.000	1999.992	83.3	624	14961
Office	1584		0	0.083		2.000	263.999	11.0	83	1975
Parking Lot	23041		0	0.083		2.000	3840.193	160.0	1197	28727
Ground (Silt Loam[5], 0-4% slope[4])	54938		0.5	0		0	0	0	0	0
								Total	31.7	45663
									gpm	gal

Table A-7: CN Method
25-Year Peak Discharge Runoff Calculations

25 YEAR Storm -- 4 in over 24 hrs		*CN Method								
	Surface Area	Rate of Rainfall	Infiltration Rate	Runoff	Storm Duration	Runoff	Volume of Runoff	Rate Volume of Runoff	Runoff Rate	Total Runoff
	ft^2	in/hour	in/hour	in/hour	hours	in	ft^3	ft^3/hr	gpm	gal
Wearhouse	12000	0.167	0	0.167	24	4.000	4000.080	166.7	1247	29923
Office	1584		0	0.167		4.000	528.011	22.0	165	3950
Parking Lot	23041		0	0.167		4.000	7680.487	320.0	2394	57455
Ground (Silt Loam[5], 0-4% slope[4])	54938		0.5	0		0	0	0	0	0
								Total	63.4	91328
									gpm	gal

RUNOFF DATA

Table A-6: McKeesport Precipitation Data May 1st, 2014 - October 31st, 2014

Time	Rainfall	Rainfall	Rainfall
(Days)	(in./100)	(in.)	(ft.)
1-May-14	175	6.890	0.574
2-May-14	5	0.197	0.016
3-May-14	0	0.000	0.000
4-May-14	38	1.496	0.125
5-May-14	0	0.000	0.000
6-May-14	0	0.000	0.000
7-May-14	0	0.000	0.000
8-May-14	46	1.811	0.151
9-May-14	0	0.000	0.000
10-May-14	0	0.000	0.000
11-May-14	109	4.291	0.358
12-May-14	0	0.000	0.000
13-May-14	292	11.496	0.958
14-May-14	0	0.000	0.000
15-May-14	13	0.512	0.043
16-May-14	259	10.197	0.850
17-May-14	58	2.283	0.190
18-May-14	38	1.496	0.125
19-May-14	0	0.000	0.000
20-May-14	0	0.000	0.000
21-May-14	0	0.000	0.000
22-May-14	0	0.000	0.000
23-May-14	0	0.000	0.000
24-May-14	0	0.000	0.000
25-May-14	0	0.000	0.000
26-May-14	0	0.000	0.000
27-May-14	0	0.000	0.000
28-May-14	259	10.197	0.850
29-May-14	36	1.417	0.118
30-May-14	5	0.197	0.016
31-May-14	0	0.000	0.000
1-Jun-14	0	0.000	0.000
2-Jun-14	0	0.000	0.000
3-Jun-14	0	0.000	0.000
4-Jun-14	102	4.016	0.335
5-Jun-14	84	3.307	0.276

6-Jun-14	0	0.000	0.000
7-Jun-14	0	0.000	0.000
8-Jun-14	0	0.000	0.000
9-Jun-14	33	1.299	0.108
10-Jun-14	0	0.000	0.000
11-Jun-14	5	0.197	0.016
12-Jun-14	274	10.787	0.899
13-Jun-14	102	4.016	0.335
14-Jun-14	152	5.984	0.499
15-Jun-14	0	0.000	0.000
16-Jun-14	0	0.000	0.000
17-Jun-14	0	0.000	0.000
18-Jun-14	0	0.000	0.000
19-Jun-14	191	7.520	0.627
20-Jun-14	61	2.402	0.200
21-Jun-14	152	5.984	0.499
22-Jun-14	13	0.512	0.043
23-Jun-14	0	0.000	0.000
24-Jun-14	5	0.197	0.016
25-Jun-14	119	4.685	0.390
26-Jun-14	84	3.307	0.276
27-Jun-14	0	0.000	0.000
28-Jun-14	0	0.000	0.000
29-Jun-14	178	7.008	0.584
30-Jun-14	102	4.016	0.335
1-Jul-14	0	0.000	0.000
2-Jul-14	0	0.000	0.000
3-Jul-14	0	0.000	0.000
4-Jul-14	0	0.000	0.000
5-Jul-14	0	0.000	0.000
6-Jul-14	0	0.000	0.000
7-Jul-14	13	0.512	0.043
8-Jul-14	0	0.000	0.000
9-Jul-14	36	1.417	0.118
10-Jul-14	0	0.000	0.000
11-Jul-14	0	0.000	0.000
12-Jul-14	0	0.000	0.000
13-Jul-14	0	0.000	0.000
14-Jul-14	127	5.000	0.417
15-Jul-14	25	0.984	0.082
16-Jul-14	0	0.000	0.000

17-Jul-14	0	0.000	0.000
18-Jul-14	0	0.000	0.000
19-Jul-14	119	4.685	0.390
20-Jul-14	137	5.394	0.449
21-Jul-14	0	0.000	0.000
22-Jul-14	0	0.000	0.000
23-Jul-14	0	0.000	0.000
24-Jul-14	0	0.000	0.000
25-Jul-14	0	0.000	0.000
26-Jul-14	0	0.000	0.000
27-Jul-14	178	7.008	0.584
28-Jul-14	94	3.701	0.308
29-Jul-14	25	0.984	0.082
30-Jul-14	0	0.000	0.000
31-Jul-14	18	0.709	0.059
1-Aug-14	0	0.000	0.000
2-Aug-14	0	0.000	0.000
3-Aug-14	48	1.890	0.157
4-Aug-14	140	5.512	0.459
5-Aug-14	0	0.000	0.000
6-Aug-14	5	0.197	0.016
7-Aug-14	0	0.000	0.000
8-Aug-14	0	0.000	0.000
9-Aug-14	0	0.000	0.000
10-Aug-14	0	0.000	0.000
11-Aug-14	0	0.000	0.000
12-Aug-14	254	10.000	0.833
13-Aug-14	79	3.110	0.259
14-Aug-14	0	0.000	0.000
15-Aug-14	10	0.394	0.033
16-Aug-14	0	0.000	0.000
17-Aug-14	0	0.000	0.000
18-Aug-14	18	0.709	0.059
19-Aug-14	0	0.000	0.000
20-Aug-14	58	2.283	0.190
21-Aug-14	297	11.693	0.974
22-Aug-14	18	0.709	0.059
23-Aug-14	81	3.189	0.266
24-Aug-14	0	0.000	0.000
25-Aug-14	0	0.000	0.000
26-Aug-14	0	0.000	0.000

27-Aug-14	0	0.000	0.000
28-Aug-14	58	2.283	0.190
29-Aug-14	0	0.000	0.000
30-Aug-14	0	0.000	0.000
31-Aug-14	0	0.000	0.000
1-Sep-14	302	11.890	0.991
2-Sep-14	18	0.709	0.059
3-Sep-14	8	0.315	0.026
4-Sep-14	0	0.000	0.000
5-Sep-14	0	0.000	0.000
6-Sep-14	0	0.000	0.000
7-Sep-14	8	0.315	0.026
8-Sep-14	0	0.000	0.000
9-Sep-14	0	0.000	0.000
10-Sep-14	0	0.000	0.000
11-Sep-14	76	2.992	0.249
12-Sep-14	25	0.984	0.082
13-Sep-14	3	0.118	0.010
14-Sep-14	13	0.512	0.043
15-Sep-14	0	0.000	0.000
16-Sep-14	20	0.787	0.066
17-Sep-14	0	0.000	0.000
18-Sep-14	0	0.000	0.000
19-Sep-14	0	0.000	0.000
20-Sep-14	0	0.000	0.000
21-Sep-14	0	0.000	0.000
22-Sep-14	28	1.102	0.092
23-Sep-14	0	0.000	0.000
24-Sep-14	0	0.000	0.000
25-Sep-14	0	0.000	0.000
26-Sep-14	0	0.000	0.000
27-Sep-14	0	0.000	0.000
28-Sep-14	0	0.000	0.000
29-Sep-14	0	0.000	0.000
30-Sep-14	0	0.000	0.000
1-Oct-14	8	0.315	0.026
2-Oct-14	0	0.000	0.000
3-Oct-14	0	0.000	0.000
4-Oct-14	76	2.992	0.249
5-Oct-14	13	0.512	0.043
6-Oct-14	0	0.000	0.000

7-Oct-14	25	0.984	0.082
8-Oct-14	102	4.016	0.335
9-Oct-14	0	0.000	0.000
10-Oct-14	0	0.000	0.000
11-Oct-14	13	0.512	0.043
12-Oct-14	0	0.000	0.000
13-Oct-14	0	0.000	0.000
14-Oct-14	23	0.906	0.075
15-Oct-14	249	9.803	0.817
16-Oct-14	5	0.197	0.016
17-Oct-14	38	1.496	0.125
18-Oct-14	0	0.000	0.000
19-Oct-14	30	1.181	0.098
20-Oct-14	0	0.000	0.000
21-Oct-14	18	0.709	0.059
22-Oct-14	33	1.299	0.108
23-Oct-14	0	0.000	0.000
24-Oct-14	0	0.000	0.000
25-Oct-14	0	0.000	0.000
26-Oct-14	0	0.000	0.000
27-Oct-14	0	0.000	0.000
28-Oct-14	0	0.000	0.000
29-Oct-14	5	0.197	0.016
30-Oct-14	0	0.000	0.000
31-Oct-14	0	0.000	0.000

Figure A-7: Pittsburgh International Airport Precipitation Data Trend (1981-2010) May 1st – October 31st

Time	Rainfall	Rainfall	Rainfall
(Days)	(in./100)	(in.)	(ft.)
1-May	0	0.000	0.000
2-May	0	0.000	0.000
3-May	118	1.180	0.098
4-May	8	0.080	0.007
5-May	0	0.000	0.000
6-May	0	0.000	0.000
7-May	0	0.000	0.000
8-May	0	0.000	0.000
9-May	0	0.000	0.000
10-May	36	0.360	0.030
11-May	0	0.000	0.000
12-May	137	1.370	0.114
13-May	0	0.000	0.000
14-May	0	0.000	0.000
15-May	3	0.030	0.003
16-May	0	0.000	0.000
17-May	0	0.000	0.000
18-May	0	0.000	0.000
19-May	0	0.000	0.000
20-May	0	0.000	0.000
21-May	38	0.380	0.032
22-May	0	0.000	0.000
23-May	202	2.020	0.168
24-May	0	0.000	0.000
25-May	199	1.990	0.166
26-May	26	0.260	0.022
27-May	86	0.860	0.072
28-May	53	0.530	0.044
29-May	3	0.030	0.003
30-May	10	0.100	0.008
31-May	0	0.000	0.000
1-Jun	38	0.380	0.032
2-Jun	71	0.710	0.059
3-Jun	3	0.030	0.003
4-Jun	0	0.000	0.000
5-Jun	3	0.030	0.003
6-Jun	8	0.080	0.007
7-Jun	28	0.280	0.023
8-Jun	0	0.000	0.000
9-Jun	0	0.000	0.000
10-Jun	0	0.000	0.000
11-Jun	8	0.080	0.007

12-Jun	28	0.280	0.023
13-Jun	0	0.000	0.000
14-Jun	0	0.000	0.000
15-Jun	0	0.000	0.000
16-Jun	13	0.130	0.011
17-Jun	66	0.660	0.055
18-Jun	0	0.000	0.000
19-Jun	0	0.000	0.000
20-Jun	3	0.030	0.003
21-Jun	3	0.030	0.003
22-Jun	0	0.000	0.000
23-Jun	6	0.060	0.005
24-Jun	5	0.050	0.004
25-Jun	0	0.000	0.000
26-Jun	0	0.000	0.000
27-Jun	0	0.000	0.000
28-Jun	0	0.000	0.000
29-Jun	0	0.000	0.000
30-Jun	48	0.480	0.040
1-Jul	0	0.000	0.000
2-Jul	145	1.450	0.121
3-Jul	0	0.000	0.000
4-Jul	0	0.000	0.000
5-Jul	0	0.000	0.000
6-Jul	0	0.000	0.000
7-Jul	3	0.030	0.003
8-Jul	143	1.430	0.119
9-Jul	454	4.540	0.378
10-Jul	0	0.000	0.000
11-Jul	63	0.630	0.053
12-Jul	8	0.080	0.007
13-Jul	130	1.300	0.108
14-Jul	0	0.000	0.000
15-Jul	0	0.000	0.000
16-Jul	16	0.160	0.013
17-Jul	0	0.000	0.000
18-Jul	0	0.000	0.000
19-Jul	0	0.000	0.000
20-Jul	69	0.690	0.058
21-Jul	0	0.000	0.000
22-Jul	0	0.000	0.000
23-Jul	0	0.000	0.000
24-Jul	0	0.000	0.000
25-Jul	0	0.000	0.000
26-Jul	5	0.050	0.004
27-Jul	0	0.000	0.000

28-Jul	0	0.000	0.000
29-Jul	28	0.280	0.023
30-Jul	0	0.000	0.000
31-Jul	0	0.000	0.000
1-Aug	0	0.000	0.000
2-Aug	0	0.000	0.000
3-Aug	0	0.000	0.000
4-Aug	0	0.000	0.000
5-Aug	0	0.000	0.000
6-Aug	20	0.200	0.017
7-Aug	0	0.000	0.000
8-Aug	0	0.000	0.000
9-Aug	0	0.000	0.000
10-Aug	0	0.000	0.000
11-Aug	0	0.000	0.000
12-Aug	0	0.000	0.000
13-Aug	0	0.000	0.000
14-Aug	0	0.000	0.000
15-Aug	10	0.100	0.008
16-Aug	0	0.000	0.000
17-Aug	0	0.000	0.000
18-Aug	8	0.080	0.007
19-Aug	143	1.430	0.119
20-Aug	23	0.230	0.019
21-Aug	0	0.000	0.000
22-Aug	0	0.000	0.000
23-Aug	0	0.000	0.000
24-Aug	0	0.000	0.000
25-Aug	0	0.000	0.000
26-Aug	0	0.000	0.000
27-Aug	0	0.000	0.000
28-Aug	0	0.000	0.000
29-Aug	8	0.080	0.007
30-Aug	0	0.000	0.000
31-Aug	0	0.000	0.000
1-Sep	0	0.000	0.000
2-Sep	0	0.000	0.000
3-Sep	0	0.000	0.000
4-Sep	0	0.000	0.000
5-Sep	9	0.090	0.008
6-Sep	13	0.130	0.011
7-Sep	0	0.000	0.000
8-Sep	0	0.000	0.000
9-Sep	0	0.000	0.000
10-Sep	0	0.000	0.000
11-Sep	0	0.000	0.000

12-Sep	0	0.000	0.000
13-Sep	49	0.490	0.041
14-Sep	78	0.780	0.065
15-Sep	0	0.000	0.000
16-Sep	0	0.000	0.000
17-Sep	0	0.000	0.000
18-Sep	0	0.000	0.000
19-Sep	0	0.000	0.000
20-Sep	0	0.000	0.000
21-Sep	233	2.330	0.194
22-Sep	0	0.000	0.000
23-Sep	0	0.000	0.000
24-Sep	0	0.000	0.000
25-Sep	0	0.000	0.000
26-Sep	0	0.000	0.000
27-Sep	16	0.160	0.013
28-Sep	458	4.580	0.382
29-Sep	25	0.250	0.021
30-Sep	0	0.000	0.000
1-Oct	20	0.200	0.017
2-Oct	5	0.050	0.004
3-Oct	0	0.000	0.000
4-Oct	0	0.000	0.000
5-Oct	0	0.000	0.000
6-Oct	95	0.950	0.079
7-Oct	0	0.000	0.000
8-Oct	6	0.060	0.005
9-Oct	0	0.000	0.000
10-Oct	0	0.000	0.000
11-Oct	0	0.000	0.000
12-Oct	0	0.000	0.000
13-Oct	0	0.000	0.000
14-Oct	0	0.000	0.000
15-Oct	0	0.000	0.000
16-Oct	0	0.000	0.000
17-Oct	0	0.000	0.000
18-Oct	23	0.230	0.019
19-Oct	3	0.030	0.003
20-Oct	0	0.000	0.000
21-Oct	0	0.000	0.000
22-Oct	32	0.320	0.027
23-Oct	92	0.920	0.077
24-Oct	0	0.000	0.000
25-Oct	3	0.030	0.003
26-Oct	64	0.640	0.053
27-Oct	32	0.320	0.027

28-Oct	3	0.030	0.003
29-Oct	0	0.000	0.000
30-Oct	0	0.000	0.000
31-Oct	0	0.000	0.000

B. APPENDIX B

TANK CAPACITY ANALYSIS

Table B-1: Analysis of Various Tank Capacities for Capacity and Overflow Trends

Tank Size	Pct. Full	Pct. Empty	Pct. Either	Value of Cooling Potential ($)	Total Overflow	average overflow	max overflow
(gallons)	%	%	%	Assumed: EER = 7	(gallons)	(gallons)	(gallons)
1,000	13%	68%	82%	$404.48	205174	47	933
2,000	11%	66%	77%	$499.58	179745	41	917
3,000	10%	63%	73%	$559.59	160360	37	917
4,000	9%	60%	69%	$611.43	143346	33	917
5,000	8%	59%	66%	$649.21	129530	29	917
6,000	7%	57%	64%	$678.28	117531	27	917
7,000	6%	56%	62%	$710.13	105532	24	917
8,000	6%	54%	60%	$738.32	93605	21	917
9,000	5%	52%	57%	$763.97	82876	19	917
10,000	5%	51%	56%	$786.46	73409	17	917
11,000	4%	50%	54%	$803.90	65394	15	917
12,000	4%	50%	53%	$821.26	57866	13	917
13,000	3%	49%	52%	$839.34	50866	12	917
14,000	3%	48%	51%	$859.60	43941	10	917
15,000	3%	47%	50%	$873.42	37942	9	917
16,000	3%	47%	49%	$886.23	33271	8	917
17,000	2%	46%	49%	$896.65	29271	7	917
18,000	2%	46%	48%	$903.60	26213	6	917
19,000	2%	46%	47%	$910.46	23213	5	914
20,000	1%	45%	47%	$916.76	20214	5	914
21,000	1%	45%	46%	$923.74	17214	4	745
22,000	1%	45%	46%	$930.71	14477	3	745
23,000	1%	45%	45%	$935.71	12477	3	745
24,000	1%	44%	45%	$939.55	10477	2	745
25,000	1%	44%	45%	$945.53	8477	2	745

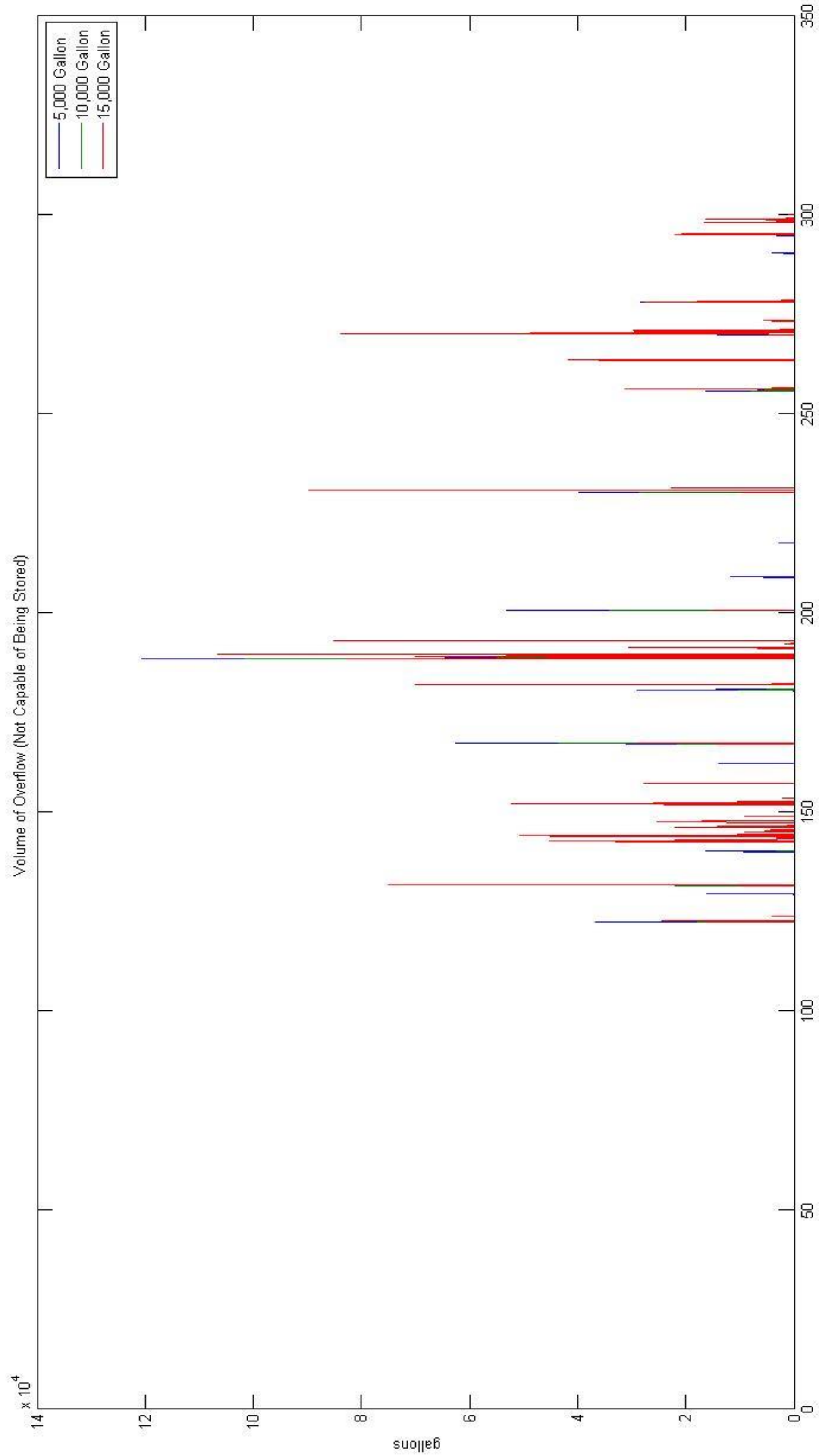

Figure B-1: Tank Overflow Trends

TANK CAPACITY COST EVALUATION

Table B-2: 5,000 Gallon Tank Cost Evaluation

5,000 Gallons	$ -						
	Before Tax Cash Flow				After Tax Cash Flow		
Year	BTCF	Depriciation	Taxable Savings	Tax	ATCF	Accumulating Value	Present Worth
0	$ (16,772.20)		$ -	$ -	$ (16,772.20)	$ (16,772.20)	$ 5,860.18
1	$641.29	$ (628.96)	$ 12.33	$ (4.19)	$ 637.10	$ (16,135.10)	
2	$641.29	$ (1,210.79)	$ (569.50)	$ 193.63	$ 834.92	$ (15,300.18)	Time for ROI:
3	$641.29	$ (1,119.88)	$ (478.59)	$ 162.72	$ 804.01	$ (14,496.17)	(Not within 15)
4	$641.29	$ (1,036.02)	$ (394.73)	$ 134.21	$ 775.50	$ (13,720.68)	Year = 27
5	$641.29	$ (958.20)	$ (316.91)	$ 107.75	$ 749.04	$ (12,971.64)	
6	$641.29	$ (886.41)	$ (245.12)	$ 83.34	$ 724.63	$ (12,247.01)	
7	$641.29	$ (819.83)	$ (178.54)	$ 60.70	$ 701.99	$ (11,545.02)	
8	$641.29	$ (758.44)	$ (117.15)	$ 39.83	$ 681.12	$ (10,863.89)	
9	$641.29	$ (748.38)	$ (107.09)	$ 36.41	$ 677.70	$ (10,186.20)	
10	$641.29	$ (748.21)	$ (106.92)	$ 36.35	$ 677.64	$ (9,508.55)	
11	$641.29	$ (748.38)	$ (107.09)	$ 36.41	$ 677.70	$ (8,830.85)	
12	$641.29	$ (748.21)	$ (106.92)	$ 36.35	$ 677.64	$ (8,153.21)	
13	$641.29	$ (748.21)	$ (106.92)	$ 36.35	$ 677.64	$ (7,475.57)	
14	$641.29	$ (748.21)	$ (106.92)	$ 36.35	$ 677.64	$ (6,797.93)	
15	$641.29	$ (748.21)	$ (106.92)	$ 36.35	$ 677.64	$ (6,120.29)	
16	$641.29	$ (748.21)	$ (106.92)	$ 36.35	$ 677.64	$ (5,442.64)	
17	$641.29	$ (748.21)	$ (106.92)	$ 36.35	$ 677.64	$ (4,765.00)	
18	$641.29	$ (748.21)	$ (106.92)	$ 36.35	$ 677.64	$ (4,087.36)	
19	$641.29	$ (748.21)	$ (106.92)	$ 36.35	$ 677.64	$ (3,409.72)	
20	$641.29	$ (748.21)	$ (106.92)	$ 36.35	$ 677.64	$ (2,732.08)	
21	$641.29	$ (374.19)	$ 267.10	$ (90.81)	$ 550.48	$ (2,181.60)	
22	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ (1,758.35)	
23	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ (1,335.10)	
24	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ (911.85)	
25	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ (488.60)	
26	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ (65.34)	
27	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 357.91	
28	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 781.16	
29	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 1,204.41	
30	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 1,627.66	
31	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 2,050.91	
32	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 2,474.16	
33	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 2,897.42	
34	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 3,320.67	
35	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 3,743.92	
36	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 4,167.17	
37	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 4,590.42	
38	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 5,013.67	
39	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 5,436.92	
40	$641.29	$ -	$ 641.29	$ (218.04)	$ 423.25	$ 5,860.18	

* "( )" denotes negative value

Table B-3: 10,000 Gallon Tank Cost Evaluation

10,000 Gallons	$ -						
	Before Tax Cash Flow				After Tax Cash Flow		
Year	BTCF	Depriciation	Taxable Savings	Tax	ATCF	Accumulating Value	Present Worth
0	$ (24,027.70)		$ -	$ -	$ (24,027.70)	$ (24,027.70)	$ 3,819.52
1	$786.46	$ (901.04)	$ (114.58)	$ -	$ 786.46	$ (23,241.24)	
2	$786.46	$ (1,734.56)	$ (948.10)	$ 322.35	$ 1,108.81	$ (22,132.43)	Time for ROI:
3	$786.46	$ (1,604.33)	$ (817.87)	$ 278.08	$ 1,064.54	$ (21,067.89)	(Not within 15)
4	$786.46	$ (1,484.19)	$ (697.73)	$ 237.23	$ 1,023.69	$ (20,044.20)	Year = 33
5	$786.46	$ (1,372.70)	$ (586.24)	$ 199.32	$ 985.78	$ (19,058.42)	
6	$786.46	$ (1,269.86)	$ (483.40)	$ 164.36	$ 950.82	$ (18,107.60)	
7	$786.46	$ (1,174.47)	$ (388.01)	$ 131.92	$ 918.38	$ (17,189.22)	
8	$786.46	$ (1,086.53)	$ (300.07)	$ 102.02	$ 888.48	$ (16,300.73)	
9	$786.46	$ (1,072.12)	$ (285.66)	$ 97.12	$ 883.58	$ (15,417.15)	
10	$786.46	$ (1,071.88)	$ (285.42)	$ 97.04	$ 883.50	$ (14,533.65)	
11	$786.46	$ (1,072.12)	$ (285.66)	$ 97.12	$ 883.58	$ (13,650.07)	
12	$786.46	$ (748.21)	$ 38.25	$ (13.01)	$ 773.45	$ (12,876.61)	
13	$786.46	$ (748.21)	$ 38.25	$ (13.01)	$ 773.45	$ (12,103.16)	
14	$786.46	$ (748.21)	$ 38.25	$ (13.01)	$ 773.45	$ (11,329.70)	
15	$786.46	$ (748.21)	$ 38.25	$ (13.01)	$ 773.45	$ (10,556.25)	
16	$786.46	$ (748.21)	$ 38.25	$ (13.01)	$ 773.45	$ (9,782.79)	
17	$786.46	$ (748.21)	$ 38.25	$ (13.01)	$ 773.45	$ (9,009.34)	
18	$786.46	$ (748.21)	$ 38.25	$ (13.01)	$ 773.45	$ (8,235.89)	
19	$786.46	$ (748.21)	$ 38.25	$ (13.01)	$ 773.45	$ (7,462.43)	
20	$786.46	$ (748.21)	$ 38.25	$ (13.01)	$ 773.45	$ (6,688.98)	
21	$786.46	$ (374.19)	$ 412.27	$ (140.17)	$ 646.29	$ (6,042.69)	
22	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ (5,523.63)	
23	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ (5,004.56)	
24	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ (4,485.50)	
25	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ (3,966.44)	
26	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ (3,447.37)	
27	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ (2,928.31)	
28	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ (2,409.24)	
29	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ (1,890.18)	
30	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ (1,371.12)	
31	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ (852.05)	
32	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ (332.99)	
33	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ 186.07	
34	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ 705.14	
35	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ 1,224.20	
36	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ 1,743.26	
37	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ 2,262.33	
38	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ 2,781.39	
39	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ 3,300.46	
40	$786.46	$ -	$ 786.46	$ (267.40)	$ 519.06	$ 3,819.52	

* "( )" denotes negative value

ALTERNATIVE STORAGE OPTIONS

As an additional consideration on the topic of storage tanks, a building owner could also consider purchasing a backup water bladder that could sit inactive with nearly no footprint when the main tank cannot contain all of the water. In the instance of a large storm when collecting the water is the most difficult a flexible storage container can be installed above ground to allow for the collection of overflow form the primary underground tank. This bladder could be deployed to contain an additional 25,000 to 30,000 gallons of water [73]. An example of these types of bladders can be found in Figure B-2 below.

Figure B-2: Example of Water Storage Bladder [73].

The costs of these bladders range from approximately $300 to $12,000 for volumes of 25 to 30,000 gallons. The incorporation of a bladder could be thought of as insurance. The more coverage, or capacity, the customer wants, the more they will need to invest.

C. APPENDIX C

SELECTED PUMP SPECIFCATIONS

Table C-1: Franklin J-Class Electric Series V Submersible Well Pump (25 GPM – 1 HP - 230 Volts - 2 Wire – 9520252 – 6 stage Wet End – High Quality Thermoplastic Resins) [61]

Pump / Equipment Type	Submersible - Complete
Multi-Stage	Yes
Horsepower Rated	1 hp
Voltage	230 Volt
GPM Range	21 to 30 gpm
Total Dynamic Head	101 to 150 ft
Brand	Franklin Electric
SKU	95202520
Stock Status	Typically In Stock (Ships in 1 to 2 Business Days)
Model #	25JV15P4-2W230

Figure C-1: Franklin J-Class Electric Series V Submersible Well Pump

Table C-2: Calculated Pump Parameters

PUMP SIZING				
Pump Shaft Power (Ws)	Max Flowrate (Q)	Horsepower (Hp)	ρ	Efficiency of Pump (*n*)
[Watts]	[ft^3/s]	[ft*lb/s]	[lb/ft^3]	[ft H2O]
107.09	0.0512	550.00	62.4	0.51

D. APPENDIX D

PIPE DESIGN

Table D-1: Pipe Design and Calculations

PIPE LAYOUT & DESIGN

Section	Flowrate (Q) [gpm]	Flowrate (Q) [ft^3/s]	Pipe Diameter (D) [in.]	Equivalent Length (Le) Ref. Table 10 [ft]	Length (L) [ft]	L/100 [ft]	V_max [ft/s]	Selected Fittings Ref Table 10 and Figure 7	Δp [ft/100ft]	Δp [ft. H2O]	Area of [ft^2]	Area of [in^2]	Holes Dia. [in]	Δp of Holes [ft. H2O]
1 (Supply)	23.00	0.0512	1.5	-	1	0.01	4	Schedule 80 PVC	5	0.05	-	-	-	-
2	90deg Elbow	90deg Elbow	1.5	2.80	-	-	4	90 deg Elbow Schedule 80 PVC	4.4	0.1232	-	-	-	-
3	23.00	0.0512	1.5	-	30	0.3	4	Schedule 80 PVC	5	1.5	-	-	-	-
4	90deg Elbow	90deg Elbow	1.5	2.80	-	-	4	90 deg Elbow Schedule 80 PVC	4.4	0.1232	-	-	-	-
5	90deg Elbow	90deg Elbow	1.5	2.80	-	-	4	90 deg Elbow Schedule 80 PVC	4.4	0.1232	-	-	-	-
6	Tee	Tee	1.25	8.20	-	-	4	Tee (one input, two output) Schedule 80 PVC	3.7	0.3034	-	-	-	-
7	90deg Elbow	90deg Elbow	1.25	2.05	-	-	4	90 deg Elbow Schedule 80 PVC	3.7	0.07585	-	-	-	-
8	90deg Elbow	90deg Elbow	1.25	2.05	-	-	4	90 deg Elbow Schedule 80 PVC	3.7	0.07585	-	-	-	-
9	11.50	0.0256	1.25	-	50	0.5	3	Schedule 80 PVC	3	1.5	0.0001139	0.01640	0.14	0
10	7.67	0.0171	1	-	50	0.5	3.5	Schedule 80 PVC	7.5	3.75	0.0000651	0.00937	0.11	0
11	3.83	0.0085	0.75	-	50	0.5	3	Schedule 80 PVC	6.5	3.25	0.0000380	0.00547	0.08	0.25
12 (pump to tank)	8.84		1	-	6.5	0.065	4	Schedule 80 PVC	8	0.52	-	-	-	-
13 (same as 7)	90deg Elbow	90deg Elbow	1.25	2.05	-	-	4	90 deg Elbow Schedule 80 PVC	3.7	0.07585	-	-	-	-
14 (same as 8)	90deg Elbow	90deg Elbow	1.25	2.05	-	-	4	90 deg Elbow Schedule 80 PVC	3.7	0.07585	-	-	-	-
15 (same as 9)	11.50	0.0256	1.25	-	50	0.5	3	Schedule 80 PVC	3	1.5	0.0001139	0.01640	0.14	0
16 (same as 10)	7.67	0.0171	1	-	50	0.5	3.5	Schedule 80 PVC	7.5	3.75	0.0000651	0.00937	0.11	0
17 (same as 11)	3.83	0.0085	0.75	-	50	0.5	3	Schedule 80 PVC	6.5	3.25	0.0000380	0.00547	0.08	0.25

*Assumed head loss to account for holes along horizontal pipe

*Reference: ASHRAE Handbook Fundamentals - 2005 - IP Edition

*Can select schedule 40 for cheaper installation

Total Head Loss: 20.05 — *Assume: 75 — *holes will be drilled in each 50' segment of horizontal pipe along roof

Approx. Head Loss: 20

(2)

Total Length of Pipe (including equivalent length of connections): 362.3 ft.

essure = 24.63 psi

*Calculated at the pump discharge

Final Total Head Loss (including elevation head): 56.8 ft H2O

Approx. Final Total Head Loss: 57 ft H2O

*A=Q/V

* Assume 36.8 ft of elevation head

E. APPENDIX E

ENERGY EVALUTATION OF EVAPORATIVE COOLING POTENTIAL

Table E-1: Heat Extraction Evaluation of Rooftop

Day	Maximum Heat Drawn From Building	Heat Drawn	Electrical Equivalent
(of the year)	(BTU)	(kW)	($)
121	3152614	924	$73.92
122	2107936	618	$49.42
123	1500677	440	$35.18
124	1411762	414	$33.10
125	3282499	962	$76.96
126	5538519	1623	$129.85
127	5426818	1590	$127.24
128	5289609	1550	$124.02
129	2261816	663	$53.03
130	3291317	965	$77.17
131	2555006	749	$59.90
132	1380537	405	$32.37
133	2710717	794	$63.55
134	3482311	1021	$81.65
135	3927222	1151	$92.08
136	3085463	904	$72.34
137	3824403	1121	$89.67
138	4334934	1270	$101.64
139	4658122	1365	$109.21
140	4095989	1200	$96.03
141	2579221	756	$60.47
142	957918	281	$22.46
143	1259433	369	$29.53
144	835034	245	$19.58
145	878347	257	$20.59
146	975082	286	$22.86
147	1048799	307	$24.59
148	1475377	432	$34.59
149	1929506	565	$45.24
150	1783799	523	$41.82
151	1381575	405	$32.39
152	798739	234	$18.73
153	1262103	370	$29.59
154	1335179	391	$31.30
155	1702650	499	$39.92
156	441179	129	$10.34
157	1219746	357	$28.60
158	3950086	1158	$92.61

159	4040259	1184	$94.73
160	3841959	1126	$90.08
161	2760394	809	$64.72
162	3182956	933	$74.63
163	3569045	1046	$83.68
164	3303314	968	$77.45
165	4588070	1345	$107.57
166	2553776	748	$59.88
167	6176955	1810	$144.82
168	2821569	827	$66.15
169	5610829	1644	$131.55
170	2680506	786	$62.85
171	2437258	714	$57.14
172	2000375	586	$46.90
173	753561	221	$17.67
174	1894359	555	$44.41
175	2613959	766	$61.29
176	2726911	799	$63.93
177	3075306	901	$72.10
178	4507973	1321	$105.69
179	3269621	958	$76.66
180	2363252	693	$55.41
181	1998830	586	$46.86
182	4127102	1210	$96.76
183	4669125	1368	$109.47
184	4508941	1321	$105.72
185	5315945	1558	$124.64
186	5580451	1635	$130.84
187	4869907	1427	$114.18
188	2334525	684	$54.73
189	3533442	1036	$82.84
190	2859841	838	$67.05
191	1480584	434	$34.71
192	4112072	1205	$96.41
193	3619498	1061	$84.86
194	6543976	1918	$153.43
195	2742618	804	$64.30
196	1980091	580	$46.42
197	4304679	1262	$100.93
198	6183738	1812	$144.98
199	3294278	965	$77.24
200	4055702	1189	$95.09
201	3512310	1029	$82.35
202	4712041	1381	$110.48
203	4165757	1221	$97.67
204	2836396	831	$66.50

205	3539901	1037	$83.00
206	3738365	1096	$87.65
207	3261900	956	$76.48
208	3304260	968	$77.47
209	3279386	961	$76.89
210	4109700	1204	$96.35
211	3167425	928	$74.26
212	2240971	657	$52.54
213	3966147	1162	$92.99
214	4868537	1427	$114.15
215	4716057	1382	$110.57
216	3586112	1051	$84.08
217	2621892	768	$61.47
218	2875402	843	$67.42
219	1947465	571	$45.66
220	2615166	766	$61.31
221	2802519	821	$65.71
222	2456022	720	$57.58
223	2833340	830	$66.43
224	3540052	1037	$83.00
225	3636932	1066	$85.27
226	2991290	877	$70.13
227	4017252	1177	$94.19
228	4543854	1332	$106.53
229	2644263	775	$62.00
230	1189678	349	$27.89
231	2166637	635	$50.80
232	5455889	1599	$127.92
233	2253420	660	$52.83
234	3215761	942	$75.40
235	3195375	936	$74.92
236	3926287	1151	$92.05
237	2884954	846	$67.64
238	3164207	927	$74.19
239	3398540	996	$79.68
240	3801363	1114	$89.13
241	7537600	2209	$176.72
242	4316410	1265	$101.20
243	3460709	1014	$81.14
244	3224917	945	$75.61
245	2203213	646	$51.66
246	1944043	570	$45.58
247	2647555	776	$62.07
248	4965155	1455	$116.41
249	3331717	976	$78.11
250	2665052	781	$62.48

251	1433771	420	$33.62
252	2991161	877	$70.13
253	1738578	510	$40.76
254	2303857	675	$54.02
255	3903908	1144	$91.53
256	2244186	658	$52.62
257	2044266	599	$47.93
258	1257741	369	$29.49
259	1739296	510	$40.78
260	1953586	573	$45.80
261	3044407	892	$71.38
262	2024864	593	$47.47
263	831867	244	$19.50
264	2283229	669	$53.53
265	2334457	684	$54.73
266	2184147	640	$51.21
267	1580754	463	$37.06
268	2055945	603	$48.20
269	2301010	674	$53.95
270	768303	225	$18.01
271	797327	234	$18.69
272	798873	234	$18.73
273	3992888	1170	$93.62
274	1698721	498	$39.83
275	1256219	368	$29.45
276	1423455	417	$33.37
277	4013154	1176	$94.09
278	3228690	946	$75.70
279	2389747	700	$56.03
280	1591094	466	$37.30
281	1151001	337	$26.99
282	1604167	470	$37.61
283	1527815	448	$35.82
284	1582004	464	$37.09
285	2239080	656	$52.50
286	2907237	852	$68.16
287	2784295	816	$65.28
288	2036698	597	$47.75
289	1863633	546	$43.69
290	4434794	1300	$103.98
291	1918692	562	$44.98
292	3280654	961	$76.92
293	4283500	1255	$100.43
294	3333621	977	$78.16
295	1420334	416	$33.30
296	847318	248	$19.87

297	1841878	540	$43.18
298	482267	141	$11.31
299	1540456	451	$36.12
300	1566445	459	$36.73
301	1237025	363	$29.00
302	1706739	500	$40.02
303	1881418	551	$44.11
304	47911	14	$1.12

F. APPENDIX F

MATLAB CODE / Evaporation Logic

The following is a compilation of all the Matlab code that was used. As is traditional with Matlab Code, all functions must be saved separately from each other and any scripts. They must be saved within the same folder as the script (or added to the script's path). They must be named such that the file name matches the function name, appended with '.m'.

Script: SW_Script.m

```
%Stormwater Management: Roof-spray Technology
%In Collaboration with Stowmwater Evaporative Roof-spray Project/Team Effort

clc
clear
close all

%Weather (TMY3 Data)
global PIT
load('PIT.mat');

%Universal Constants
global g
g = 9.81; % m/sec^2. Acceleration due to Gravity.
global sigma
sigma = 5.67E-08; % W / (m^2 * K). Stefan-Boltzman Constant

%Electrical and A/C Values:
COPac = 1.5;         %Typical Coefficient of Performance for Air Conditioner
                     %powerknot.com  "COP's, EER's, and SEERs"
Celec = .08;         % $/kW-hr

%% Building Values
global Area
Area.Roof.Actual = 1021.93; %m^2 ~ 11000 ft^2
Area.Roof.Effective = (1/cos(atan(-1/12))) * Area.Roof.Actual;

%% Property Values
Area.Property.Total = 8506.49;
Area.Floor = Area.Roof.Actual;
Area.Property.Building = Area.Floor;
Area.Property.Blackspace = 100;
Area.Property.Greenspace = Area.Property.Total - Area.Property.Building -
Area.Property.Blackspace;

%% Material Values
%  Air (Ambient and Inside Building)
global Air
Air.TempRange = [200, 250, 300, 350]';
Air.alphaRange = [10.3E-06, 15.9E-06, 22.5E-06, 29.9E-06]';
Air.betaRange = [(1/200), (1/250), (1/300), (1/350)]';
Air.cpRange = [1.007, 1.006, 1.007, 1.009]';
Air.kRange = [18.1E-03, 22.3E-03, 26.3E-03, 30.0E-03]';
Air.muRange = [132.5E-07, 159.6E-07, 184.6E-05, 208.2E-07]';
Air.nuRange = [7.590E-06, 11.44E-06, 15.89E-06, 20.92E-06]';
```

```
Air.Prandtl = [0.737, 0.720, 0.707, 0.7]';
Air.rhoRange = [1.7458, 1.3947, 1.1614, 0.9950]';
Air.LookUpTable = [Air.TempRange, Air.alphaRange, Air.betaRange, Air.cpRange,
Air.kRange, Air.muRange, Air.nuRange, Air.Prandtl, Air.rhoRange];

%Water
global Water
Water.LookUpTable(:,1) = [273.15, 278, 283, 288, 293, 298, 303, 310, 313,
333]';
Water.LookUpTable(:,2) = (1/25.4)*[4.58, 6.54, 9.21, 12.79, 17.54, 23.76,
31.8, 47.07, 55.3, 149.4]'; %in. Hg
Water.LookUpTable(:,3) = [999.8, 1000, 999.85, 999.7, 998.95, 998.2, 996.95,
995.7, 987.7,983.2];

%   Water Vapor
global WaterVapor
WaterVapor.LookUp(:,1) = [273.15, 275, 280, 285, 290, 295, 300, 305, 310,
315]';
WaterVapor.LookUp(:,2) = [2502, 2497, 2485, 2473, 2461, 2449, 2438, 2426,
2414, 2402]';
WaterVapor.LookUp(:,3) = [1E+03, 1E+03, 1E+03, 1E+03, 1.001E+03, 1.002E+03,
1.003E+03, 1.004E+03, 1.005E+03, 1.006E+03]';

%  Aluminum (Roof & Walls)
global Aluminum;
Aluminum.cp = 0.875;
Aluminum.delta = 0.005;
Aluminum.eta = 0.82;
Aluminum.k = 0.177;
Aluminum.rho = 2770;

%roof
global Roof
Roof.Volume = Aluminum.delta * Area.Roof.Effective;
Roof.Mass = Aluminum.rho * Roof.Volume;

%  Insulation (Walls)
global Insulation;
Insulation.cp = 0.835;
Insulation.delta = 0.18;
Insulation.k = 0.038;
Insulation.rho = 32;

%  Asphalt (Blackspace)
global Asphalt
Asphalt.coefficientRunoffCollection = 0.5*(0.7 + 0.95);

%  Concrete (Floor)
global Concrete
Concrete.cp = 0.880;
Concrete.delta = 0.5;
Concrete.k = 1.4;
Concrete.rho = 2300;


%  Ground (Greenspace)
```

```
global Ground
Ground.coefficientRunoffCollection = 0.5*(0.13+0.17);
Ground.cp = 0.5*(2200 + 2500);
Ground.kpermRange = [(1-Ground.coefficientRunoffCollection)*0.0069, 0.0069];
Ground.delta = 1;
Ground.ktherm = 0.5*(0.33 + 1.4);
Ground.rho = 0.5*(1220 + 1250);
Ground.qvRange = [0, 0.5];
Ground.qv.Saturation = 0.2760;
Ground.Temp.Inf = 285.93;

%   Greenspace Collection Zone (Greenspace.CZ)
global Greenspace
Greenspace.CZ.Area = pi/16;
Greenspace.CZ.Volume = Greenspace.CZ.Area * Ground.delta;
Greenspace.CZ.Saturation.Initial = 0.25;
Greenspace.CZ.kperm = mean(Ground.kpermRange);
%   Greenspace Receiving Zone (Greenspace.RZ)
Greenspace.RZ.Area = Area.Property.Greenspace - Greenspace.CZ.Area;
Greenspace.RZ.Volume = Greenspace.RZ.Area * Ground.delta;
Greenspace.RZ.Saturation.Initial = 0.25;
Greenspace.RZ.kperm = mean(Ground.kpermRange);
%   Greenspace Ratio of Areas
Greenspace.ratioArea = Greenspace.CZ.Area / Area.Property.Greenspace;
%   Greenspace Interface Area
Greenspace.Interface.Area = Ground.delta * (sqrt(Greenspace.CZ.Area /
pi)*0.5*pi);

i = 0;

T0 = 293;               %Kelvin
startHour = 121 * 24;   %May 1
endHour = 304 * 24;     %Oct. 31

hr = 1:1:8760;
Tr = zeros(365*24 , 1);
TrDry = zeros(365*24 , 1);
Tdiff = zeros(365*24 , 1);
tinf = zeros(24,1);
mev = zeros(365*24 , 1);
vMev = zeros(365*24 , 1);
volCollected = zeros(365*24 , 1);
sumVolCollected = 0;
vSumVolCollected = zeros(365*24 , 1);
Mev = 0;
QevRoof = zeros(365*24 , 1);
sumQevRoof = 0;
vSumQevRoof = zeros(365*24 , 1);
Qac = zeros(365*24 , 1);
sumQac = 0;
vSumQac = zeros(365*24 , 1);
Qelec = zeros(365*24 , 1);
sumQelec = 0;
vSumQelec = zeros(365*24 , 1);
Cac = zeros(365*24 , 1);
sumCac = 0;
```

```
vSumCac = zeros(365*24 , 1);
t = zeros(1,24);
hours = 1:1:24;
noonHours = zeros(1,365);
PDT = zeros(1, 365);
PDTdry = zeros(i, 365);
si = 0;
summerHours = zeros(1, endHour - startHour);
summerT = zeros(1, endHour - startHour);
summerTr = zeros(1, endHour - startHour);
summerMev = zeros(1, endHour - startHour);
summerSumMev = zeros(1, endHour - startHour);
summerSumVcoll = zeros(1, endHour - startHour);

for day = 1:1:365
    for hour = 1:1:24

        i = i + 1;

        if i > 1
            T0 = Tr(i - 1);
        end

        this = findTr(i, T0);

        %rooftop temperature
        Tr(i) = this.Tr;

        %mass of evaporated water
        mev(i) = this.mEvap;    %kg
        Mev = Mev + mev(i);
        vMev(i) = Mev;

        %Rooftop Temperature without Cooling
        TrDry(i) = this.TrDry;

        %Heat drawn from the rooftop
        QevRoof(i) = 2257 * mev(i);                        %kJ

        sumQevRoof = sumQevRoof + QevRoof(i);              %kJ
        vSumQevRoof(i) = sumQevRoof;                       %kJ

        %Heat drawn from inside the building
        Qac(i) = transformQ(this.T1, this.T2, this.Tr, this.T4, this.R1,
this.R3, QevRoof(i), PIT.GHI(i));
            %kJ
        Qac(i) = Qac(i) *.000278;                        %kW-hr
        sumQac = sumQac + Qac(i);                        %kW-hr
        vSumQac(i) = sumQac;                             %kW-hr

        %Cost of Air Conditioning
        Qelec(i) = Qac(i) / COPac;                       %kW-hr
        sumQelec = sumQelec + Qelec(i);                  %kW-hr
        vSumQelec(i) = sumQelec;
        Cac(i) = Qelec(i) * Celec;                       % $
        sumCac = sumCac + Cac(i);                        % $
```

```
        vSumCac(i) = sumCac;                         % $

        %Ambient temperatures at each hour in the day:
        t(hour) = Tr(i) - 273;
        tinf(hour) = PIT.TDB(i);

        %Temperature effect of evaporation:
        Tdiff(hour) = Tr(i) - TrDry(i);

        %Calculate water collection
        volCollected(i) = waterCollected(i);    %m^3
        sumVolCollected = sumVolCollected + volCollected(i);
        vSumVolCollected(i) = sumVolCollected;


    end

    %Peak Daily Temperature
    noonHours(day) = 24 * day - 12;
    PDT(day) = max(t);
    PDTdry(day) = max(TrDry);

end

%making arrays vertical
%vMev = vMev';
mev = mev';

%volume of water evaporated in m^3
    %1000 = density of water
vVolEvap = mev / 1000;
vSumVolEvap = vMev/1000;
sumVolEvap = Mev / 1000;

%convert volumes to liters
    %1000 = conversion to liters from m^3
vVolEvap = vVolEvap * 1000;
vSumVolEvap = vSumVolEvap * 1000;
sumVolEvap = sumVolEvap * 1000;
sumVolCollected = sumVolCollected * 1000;
vSumVolCollected = vSumVolCollected * 1000;
volCollected = volCollected * 1000;

%convert Tr down to Celcius
Tr = Tr - 273;

%Trim/ make new vectors to include only the summer

summerHours = startHour:1:endHour;
summerHours = summerHours';

summerT = PIT.TDB(startHour:endHour);                     %Celcius
summerTr = Tr(startHour:endHour) - 273;                   %Celcius
vSummerSumMev = vMev(startHour:endHour) - vMev(startHour) * ones(endHour -
startHour +1,1);                %kg
```

```
vSummerSumVev = vSumVolEvap(startHour:endHour) - vSumVolEvap(startHour) .*
ones(endHour - startHour +1,1);          %liters
vSummerSumVcoll = vSumVolCollected(startHour:endHour) -
vSumVolCollected(startHour) .* ones(endHour - startHour +1,1);   %liters

%Cost of electricity:


subplot(3,1,1)
plot (summerHours,summerTr)
title('Rooftop Temperature')
xlabel('hours')
ylabel('Degrees C')

subplot(3,1,2)
plot (summerHours, vSummerSumVev, summerHours, vSummerSumVcoll);
title('Volume of Water Evaporated over a summer')
legend('Evaporated','Collected')
xlabel('hour')
ylabel('Liters')

netWater = vSumVolCollected - vSumVolEvap;
summerNetWater = vSummerSumVcoll - vSummerSumVev;

subplot(3,1,3)
plot(summerHours, summerNetWater)
title('Net water collected and evaporated')
xlabel('hour')
ylabel('Liters')


%Sizing a tank
galTankCapac = 1000:1000:50000;          %gallons
literTankCapac = galTankCapac * 3.785;    %liters

hrsFull = zeros(length(galTankCapac),1);
hrsEmpty = zeros(length(galTankCapac),1);
hrsEither = zeros(length(galTankCapac),1);
coolValueMissed = zeros(length(galTankCapac),1);
pctFull = zeros(length(galTankCapac),1);
pctEmpty = zeros(length(galTankCapac),1);
pctEither = zeros(length(galTankCapac),1);
coolingValue = zeros(length(galTankCapac),1);
summerVolEvap = zeros(length(galTankCapac),1);

for i = 1:1:length(galTankCapac)
    %For reference:
        %startHour = may 1
        %endHour = oct. 31
    h = amountInTank(startHour, endHour, literTankCapac(i), volCollected,
vVolEvap, Cac);
    hrsFull(i) = h.hrsFull;
    pctFull(i) = h.pctFull;
    hrsEmpty(i) = h.hrsEmpty;
    pctEmpty(i) = h.pctEmpty;
    hrsEither(i) = hrsEmpty(i) + hrsFull(i);
```

```
    pctEither(i) = h.pctEither;
    summerVolEvap(i) = h.volEvap;
    coolValueMissed(i) = h.coolingValueMissed;
    coolingValue(i) = h.coolingValue;
    amtInTank = h.amtInTank;
    totalOverflow(i) = h.totalOverflow;
    maxOverflow(i) = h.maxOverflow;
    averageOverflow(i) = h.averageOverflow;

    if i == 5
        fiveThGal = amtInTank / 3.785; %gallons
    elseif i == 10
        tenThGal = amtInTank / 3.785;
    elseif i == 15
        fifteenThGal = amtInTank / 3.785;
    end

end

daysFull = hrsFull / 24;
daysEmpty = hrsEmpty / 24;
daysEither = hrsEither / 24;

figure
plot(galTankCapac,daysFull)
title('Total days completely full for various tanks from May- Nov.')
xlabel('size of tank (gallons)')
ylabel('time full (days)')

fprintf('Tank Size \t Pct. Full \t Pct. Empty \t Pct. Either \t AC Value of
cooling \t total overlfow \t average overflow \t max overflow \r');
for i = 1:1:length(galTankCapac)
    fprintf('%.2f \t %.2f \t %.2f \t %.2f \t $ %.2f \t %.2f \t %.2f \t %.2f
\r',galTankCapac(i),pctFull(i),pctEmpty(i),pctEither(i),coolingValue(i),total
Overflow(i),averageOverflow(i),maxOverflow(i))
end

%Script should return the following values:
    %average, max, min evaporation rates
    %a,m,m temperatures
    %trend for fullness of 5,000, 10,000, 15,000 gal tank
        %total volume, not percentage

avgEvRate = mean(mev(startHour:endHour));  %kg/hr
maxEvRate = max(mev(startHour:endHour));   %kg/hr
minEvRate = min(mev(startHour:endHour));   %kg/hr

avgTr = mean(Tr(startHour:endHour));       %deg C
maxTr = max(Tr(startHour:endHour));
minTr = min(Tr(startHour:endHour));

fprintf('\r')

fprintf('Minimum Evaporation Rate (kg/hr) \t %.1f \r', minEvRate)
fprintf('Average Evaporation Rate (kg/hr) \t %.1f\r', avgEvRate)
fprintf('Maximum Evaporation Rate (kg/hr) \t %.1f\r', maxEvRate)
```

```
fprintf('\r')

fprintf('Minimum Rooftop Temperature (C)\t %.1f \r', minTr)
fprintf('Average Rooftop Temperature (C)\t %.1f\r', avgTr)
fprintf('Maximum Rooftop Temperature (C)\t %.1f\r', maxTr)

fprintf('Average heat extraction from building (summer): \t %.2f BTU
\r',mean(Qac))
fprintf('Maximum heat extraction from building (summer): \t %.2f BTU
\r',max(Qac))
fprintf('Total heat extraction from building (summer): \t %.2f BTU
\r',sumQac)

juneStart = 152 * 24;
juneEnd = juneStart + 31 * 24;
juneHours = juneStart:1:juneEnd;
julyStart = 213 * 24;
julyEnd = 244 * 24;
julyHours = julyStart:1:julyEnd;

allHours = 1:1:365*24;

summerDays = summerHours / 24;
dayIndex = 0;
daysVector = zeros((endHour - startHour)/24 + 1,1);
QacDays = zeros((endHour - startHour)/24 + 1,1);

for n = startHour:1:endHour

    if mod(n,24) == 0
        dayIndex = dayIndex + 1;
        daysVector(dayIndex) = dayIndex;
    end

    QacDays(dayIndex) = QacDays(dayIndex) + Qac(n);

end

fprintf('\rday\tHeat Drawn From Building (BTU) \t Heat Drawn (kW) \t AC
Loading (746) \t AC Loading (3504)\r')

for n = 1:1:length(QacDays)

    fprintf('%i \t %.2f \t %.2f \t $ %.2f \t $ %.2f
\r',n,QacDays(n),QacDays(n)/3412.14, QacDays(n)*.00366535, QacDays(n)*.01722)

end

juneDays = allHours(juneStart:juneEnd)/24;
julyDays = allHours(julyStart:julyEnd)/24;

subplot(2,2,1)
```

```
plot(summerHours,fiveThGal(startHour:endHour),summerHours,tenThGal(startHour:
endHour),summerHours,fifteenThGal(startHour:endHour))
title('Volume Witheld in Various Tank Sizes for entire summer')
xlabel('hours')
ylabel('gallons')
legend('5,000 Gallon','10,000 Gallon','15,000 Gallon')

subplot(2,2,2)
plot(juneHours,fiveThGal(juneStart:juneEnd),juneHours,tenThGal(juneStart:june
End),juneHours,fifteenThGal(juneStart:juneEnd))
title('Volume Witheld in Various Tank Sizes in June')
xlabel('hours')
ylabel('gallons')
legend('5,000 Gallon','10,000 Gallon','15,000 Gallon')

subplot(2,2,3)
plot(julyHours,fiveThGal(julyStart:julyEnd),julyHours,tenThGal(julyStart:july
End),julyHours,fifteenThGal(julyStart:julyEnd))
title('Volume Witheld in Various Tank Sizes in June')
xlabel('hours')
ylabel('gallons')
legend('5,000 Gallon','10,000 Gallon','15,000 Gallon')
```

```
function r = findTr(i,T0)
```

```
%determines the rooftop temperature using iterative techniques
%Requires global variables:
    %MGT [all]        x  TMY3 data


Tr = T0;
global PIT
To = PIT.TDB(i) + 273;
Ti = 298; %Kelvin
j = 0;

while abs(Tr - T0) / Tr > 0.01  ||  j == 0
    j = j + 1;

    Ri = calcRi(Tr, i);
    Ro = calcRo(Tr, i);

    Qrad = calcQrad(i);

    ev = calcQevap(i , Tr);
    Qev = ev(1);
    mev = ev(2);

    T0 = Tr;
    Tr = (Ri.equiv * Ro) / (Ri.equiv + Ro) * (Ti/Ri.equiv + To/Ro + Qrad - 
Qev);
    TrDry = (Ri.equiv * Ro) / (Ri.equiv + Ro) * (Ti/Ri.equiv + To/Ro + Qrad);

end

T2 = Ti - (Ti - Tr) * Ri.conv / (Ri.conv + Ri.cond);


r.Tr = Tr;
r.mEvap = mev;
r.TrDry = TrDry;
r.R1 = Ri.conv;
r.R2 = Ri.cond;
r.R3 = Ro;
r.T1 = Ti;
r.T2 = T2;
r.T4 = To;


end


function r = amountInTank(startHour, endHour, tankSize, litersCollected, 
litersEvap, airCondCost)

vol = 0;
volEvap = 0;
hoursFull = 0;
hoursEmpty = 0;
aVol = zeros(365*24,1);
```

```matlab
valueMissed = 0;
coolingValue = 0;
sumOverflow = 0;

for i = startHour:1:endHour

    aVol(i) = vol;

    if vol + litersCollected(i) - litersEvap(i) >= tankSize
        %The tank fills up this hour
        hoursFull = hoursFull + 1;

        coolingValue = coolingValue + airCondCost(i);

        overflow =  vol + litersCollected(i) - litersEvap(i) - tankSize;
        vOverflow(i) = overflow;
        sumOverflow = sumOverflow + overflow;

        volEvap = volEvap + litersEvap(i);

        vol = tankSize;

    elseif vol + litersCollected(i) - litersEvap(i) <= 0
        %The tank empties out this hour
        hoursEmpty = hoursEmpty + 1;

        valueMissed = valueMissed + airCondCost(i);

        volEvap = volEvap + vol;

        vol = 0;

    else
        %The tank has water, but is not full

        vol = vol + litersCollected(i) - litersEvap(i);

        volEvap = volEvap + litersEvap(i);

        coolingValue = coolingValue + airCondCost(i);

    end
end

maxOverflow = max(vOverflow);

r.hrsFull = hoursFull;
r.hrsEmpty = hoursEmpty;
r.pctEmpty = hoursEmpty / (endHour - startHour);
r.pctFull = hoursFull / (endHour - startHour);
r.pctEither = (hoursFull + hoursEmpty)/(endHour - startHour);
r.amtInTank = aVol;
r.coolingValueMissed = valueMissed;
r.coolingValue = coolingValue;
r.volEvap = volEvap;
```

```
r.totalOverflow = sumOverflow;
r.averageOverflow = sumOverflow / (endHour - startHour);
r.maxOverflow = maxOverflow;


end


function r = averageRainyDay(dailyRain)

numDays = 0;
sumRain = 0;

for i = 1:1:365
    if dailyRain(i) > 0

        numDays = numDays + 1;
        sumRain = sumRain + dailyRain(i);

    end
end

r = sumRain / numDays;
end
```

```
function r = calcQevap(i, Tr)
%Calculates the rate of evaporative cooling via water on the roof.
%Requires global variables:
    % PIT                   TMY3 Data structure
    % Water.LookUpTable     Matrix [[temps],[Pvapor],[density]]
    % A                     Area of roof's top surface.

%Assuming:
    %Pan Evaporation Model
    %Film of water exists at Tr, roof temperature

global PIT
global Water
global WaterVapor
global Area

A = Area.Roof.Effective;

%Atmospheric Conditions
KTinf = PIT.TDP(i) + 273;   %i is the row within the TMY3 data (what
day/time?)
KTdp = PIT.TDP(i) + 273;    %K
GHI = PIT.GHI(i);           %kW
Wsp = PIT.WindSpeed(i);     %m/s
RH = PIT.RH(i) / 100;       %Percent
Pinf = PIT.Patm(i);         %mBar
    Pinf = Pinf * 100;      %Pa


if KTinf > 273  && Tr > 273
    %disp('calculating evaporation')
    %disp(i)

    %Evap Model From SW Report:
    Pws = exp(77.345 + 0.0067 * KTinf - 7235/KTinf)/(KTinf^8.2);
        %Tinf;      K
        %Pws;       Pa

    Pw = RH * Pws;
        %Omega;

    Xs = (0.62389 * Pws) / (Pinf - Pws);

    X = (0.62389 * Pw) / (Pinf - Pw);

    Theta = 25 + 19 * Wsp;

    Tfilm = .5 * (KTinf + Tr);

    hfg = interp1(WaterVapor.LookUp(:,1) , WaterVapor.LookUp(:,2) , Tfilm);

    Qev = hfg * Theta * A * (Xs - X);

    mev = Theta * A * (Xs - X);
```

```
else
    %The air or rooftop temperature is below freezing
    Vev = 0;

    mev = 0;

    Qev = 0;
end

r(1) = Qev;
r(2) = mev;

end



function r = calcQrad(i)

%determines the radiative HT from sunlight.
%requires global variables:
    % PIT [all]         TMY3 data structure

global PIT

r = PIT.GHI(i);
end
```

```
function r = calcRi(Troof,i)
%AA
%Calculates the thermal resistance on the internal boundary of the roof
%c.v.
%Requires global variables:
    % Air.LookUpTable     x  4x9 table of air properties at different temps.
    % Aluminum.eta        x  emissivity of aluminum
    % sigma               x  Stefan- Boltzman Constant
    % PIT                 x  Structure containing TMY3 data
    % Ar                  x  Surface Area of the top of the roof
    % Aluminum.k          x          Conduction Coefficient of Roof material
    % Aluminum.delta      x              Thickness of roof surface layer
    % Lr                  x  Characteristic Length of roof
    % Ains                x  Area of insulation
    % Insulation.k        x  Conduction Coefficient of insulation
    % Insulation.delta    x  Thickness of insulation layer
global Area
global Roof
global Air
global Aluminum
global sigma
global PIT
global Insulation
global g

Ar = Area.Roof.Effective;
Lr = Roof.Volume / Area.Roof.Effective;
Ains = Ar;

Pr = interp1(Air.LookUpTable(:,1), Air.LookUpTable(:,8), Troof);
beta = interp1(Air.LookUpTable(:,1),Air.LookUpTable(:,3), Troof);
nu = interp1(Air.LookUpTable(:,1),Air.LookUpTable(:,6), Troof);
ka = interp1(Air.LookUpTable(:,1),Air.LookUpTable(:,5), Troof);

eta = Aluminum.eta;

Tinf = 273.15 + 25;      % 25 degrees celcius
Pinf = PIT.Patm(i);      %i is the row within the TMY3 data (what day/time?)

Gr = g * beta * abs(Troof - Tinf) * (Lr ^3) / nu;
%Lr is the characteristic length of the roof

Ra = Gr * Pr;

Rcond = Aluminum.delta / (Aluminum.k * Ar) + Insulation.delta / (Insulation.k
*Ains);


if Troof > Tinf
    %upper surface, cold plate

    Nus = 0.27 * Ra ^ 0.25;
    hi = ka / Lr * Nus;
    Rconv = 1 / (hi * Ar);

elseif Troof < Tinf
    %upper surface, hot plate

    if Ra > 10^7

        Nus = 0.594 * Ra ^ 0.25;
```

```
    else

        Nus = 0.15 * Ra ^ (1/3);

    end

    hi = ka / Lr * Nus;
    Rconv = 1 / (hi * Ar);

else
    %no convection
    Rconv = 0;

end

Ri = Rconv + Rcond;

r.equiv = Ri;
r.conv = Rconv;
r.cond = Rcond;

end
```

```
function r = calcRo(Tr, i)
%AB
%Calculates the thermal resistance on the external boundary of the roof
%c.v.
%Requires global variables:
    % Air.LookUpTable      x 4x9 table of air properties at different temps.
    % Aluminum.eta         x emissivity of aluminum
    % sigma                x Stefan- Boltzman Constant
    % PIT                  x Structure containing TMY3 data
    % A                    x Surface Area of the top of the roof
    % Lr                    Characteristic Length of roof

global Air
global Aluminum
global sigma
global PIT
global Area
global Roof
global g

A = Area.Roof.Effective;
Lr = Roof.Volume / A;

Pr = interp1(Air.LookUpTable(:,1), Air.LookUpTable(:,8), Tr);
beta = interp1(Air.LookUpTable(:,1),Air.LookUpTable(:,3), Tr);
nu = interp1(Air.LookUpTable(:,1),Air.LookUpTable(:,6), Tr);
ka = interp1(Air.LookUpTable(:,1),Air.LookUpTable(:,5), Tr);

eta = Aluminum.eta;

Tinf = PIT.TDB(i);  %i is the row within the TMY3 data (what day/time?)
Pinf = PIT.Patm(i);

sig = sigma;

Gr = g * beta * (Tr - Tinf) * (Lr ^3) / nu;
%Lr is the characteristic length of the roof

Ra = Gr * Pr;

%assuming black- body radiation to space
hr = eta * sig * (Tr + Tinf) * (Tr ^2) * A;
Rrad = 1 / (hr * A);


if Tr < Tinf
    %upper surface, cold plate

    Nus = 0.27 * Ra ^ 0.25;
    ho = ka / Lr * Nus;
    Rconv = 1 / (ho * A);

    Ro = Rconv * Rrad / (Rconv + Rrad);

elseif Tr > Tinf
```

```
    %upper surface, hot plate

    if Ra > 10^7

        Nus = 0.594 * Ra ^ 0.25;

    else

        Nus = 0.15 * Ra ^ (1/3);

    end

    ho = ka / Lr * Nus;
    Rconv = 1 / (ho * A);

    Ro = Rconv * Rrad / (Rconv + Rrad);

else
    %no convection

    Ro = 1 / (hr * A);

end

r = Ro;
end


function Tf = kelvToFahr(Tk)

    Tf = (Tk - 273.115) * 1.8 + 32;

end


function r = rainPerDay()

i = 0;
rainCollected = zeros(365,1);

for day = 1:1:365
    for hour = 1:1:24

        i = i + 1;

        rainCollected(day) = rainCollected (day) + waterCollected(i);

    end
end

r = zeros(365,2);

r(:,2) = rainCollected(day);
r(:,1) = 1:1:365;
```

```
end

function r = transformQ(T1, T2, T3, T4, R1, R3, Qa, Qrad)

Qb = (T1 - T2)/R1 + (T4 - T3)/R3 - Qa + Qrad;

r = Qb;

end


function r = waterCollected(i)
    global PIT
    global Area
    global Asphalt
    global Greenspace
    global Ground

    Lprecip = PIT.LPrecip(i) / 1000;

    %% Calculate Storage Flow In
    roofPrecipitation = Lprecip * Area.Roof.Actual;
    greenspacePrecipitation = Lprecip * Area.Property.Greenspace;
    blackspacePrecipitation = Lprecip * Area.Property.Blackspace;

    %   Collect from Roof
    Roof.PrecipitationCollect = roofPrecipitation * (1);

    %   Collect from Blackspace
    Blackspace.PrecipitationCollect = blackspacePrecipitation *
Asphalt.coefficientRunoffCollection;

    %   Aggregate Collection
    Vol = Blackspace.PrecipitationCollect + Roof.PrecipitationCollect;
    %Vol is in m^3

    r = Vol;

end

Script: MakePIT.m
%Patm            mbar
%WindSpeed       m/s
%LPrecip         mm
%GHI             kW/m^2
%Temps           celcius

i = 0;
for day = 1:1:365
    for hour = 1:1:24
        i = i + 1;

        PIT.ToD(i) = hour;
```

```
    end
    PIT.Date(i) = day;

end
```

Script: misc.m

```
%This script performs miscellaneous calculations
%   for the Stormwater Management report.

clc

%Average Rainfall per Day
d = 0;
sum = 0;
dailySum = zeros((endHour - startHour)/24 + 1,1);
numDays = (endHour - startHour) / 24;
stormIndex = 0;

for i = startHour:1:endHour
     if  mod((i - startHour),24) == 0
         d = d + 1;
     end

     dailySum(d) = dailySum(d) + PIT.LPrecip(i);
     sum = sum + PIT.LPrecip(i);

     if PIT.LPrecip(i) > 0

         stormIndex = stormIndex + 1;
         pointer(stormIndex) = i;
         stormTotalRain(stormIndex) = 0;
         stormDuration(stormIndex) = 0;

         while PIT.LPrecip(i) > 0
             stormDuration(stormIndex) = stormDuration(stormIndex) + 1;
             stormTotalRain(stormIndex) = stormTotalRain(stormIndex) +
PIT.LPrecip(i);

             i = i + 1;
         end
     end
end
```

PIT is a variable that is saved to the program folder. It was directly made from the Typical Meteorological Year Data (TMY3) for Pittsburgh International Airport. The variable is a data structure where each property corresponds to the TMY3 data.

```
PIT =
          TDB: [8760x1 double]
          GHI: [8760x1 double]
          TDP: [8760x1 double]
          TWB: 0
    WindSpeed: [8760x1 double]
           RH: [8760x1 double]
         Patm: [8760x1 double]
      LPrecip: [8760x1 double]
          ToD: [8760x1 double]
         Date: [8760x1 double]
```

APPROVAL OF EXAMINNING COMMITTEE

COMMITTEE MEMBERS

Kenneth H. Means

12/11/2015

DATE